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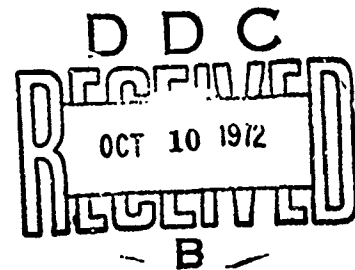
# INSPECTION OF PILE DRIVING OPERATIONS

by

M. T. Davisson

CONSTRUCTION ENGINEERING RESEARCH LABORATORY

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13. ABSTRACT <p>The inspection of pile driving operations involves the accumulation and interpretation of technical data and the simultaneous recording of pay item data. This manual is designed to explain the range of tasks inspectors must perform and to put the tasks in the broader perspective of the entire pile driving operation.</p> <p>The manual begins by explaining pre-construction organization, then the pile driving operation, and finally the data that the inspector must record. Two appendices include additional technical information on pile drivers, both the hammer and vibratory types.</p>		
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*M. T. Davisson*

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Department of the Army  
**CONSTRUCTION ENGINEERING RESEARCH LABORATORY**  
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# INSPECTION OF PILE DRIVING OPERATIONS

## 1 INTRODUCTION

**Purpose and Scope.** The manual describes the information that must be accumulated during the inspection of pile driving operations. It is assumed that the soil investigation phase is completed, that plans and specifications are finalized, and a contract written. The inspection techniques described herein are concerned primarily with technical items, but methods of incorporating information on pay items are also described.

The manual begins by explaining pre-construction organization, then the pile driving operation, and finally the data that the inspector must record. Two appendices include additional technical information on pile drivers, both the hammer and vibratory types.

**References.** The following Engineer Manuals should be available to the inspection team:

- |                |   |
|----------------|---|
| EM 385-1-1     | General Safety Requirements               |
| EM 1110-2-1803 | Subsurface Investigation of Soils         |
| EM 1110-2-2000 | Standard Practice for Concrete            |
| EM 1110-2-2906 | Design of Pile Structures and Foundations |
| TM 5-258       | Pile Construction                         |

The reference list at the end of this volume can supplement the manuals.

## 2 PRE-CONSTRUCTION ORGANIZATION

**Purpose.** There are often immediate needs at the beginning of pile driving that place a great burden on the inspection team. In many cases unknown or unanticipated factors cause piles to drive much longer or shorter than the design length or pile damage. These factors usually make their presence known in the early stages of construction and lead to investigations to determine whether the design is proper for the conditions actually encountered in the field, or whether the contractor is using proper techniques. Such investigations are based on *facts* observed in the early stages of construction; it is the duty of the inspection team to observe all pertinent facts.

If the inspection team is properly organized prior to construction, the pertinent facts will be observed automatically as standard procedure. Then, if troubles arise, an investigation to determine cause and recommend remedies can be completed with maximum speed. This in turn benefits the project schedule and minimizes losses to both contractor and owner. The benefits of thorough preconstruction organization cannot be overemphasized. Further, at the start of construction, the presence of apparently excess inspector manpower can be economically justified as a trivial cost relative to the potential losses caused by delays if trouble is encountered.

**Documents.** Prior to construction the following documents should be gathered:

1. Plans
2. Specifications
3. Contract
4. Soil Boring Data
5. Design Memoranda

The pile plans are most useful in reduced sizes. On the plans each pile should have a unique designation, usually a number or a combination of numbers and letters. Commonly, column numbers or structure designations are used to precede the pile number. It is essential that only these designations be used in communications between field and office forces on the part of both contractor and owner; otherwise confusion will result. Ordinarily the pile numbering system will be given on the engineer's plans, but the system may also be a required submittal from the contractor. If the engineer has neither supplied a numbering system nor required the contractor to submit one, the inspection team should proceed to initiate a system in coordination with both the contractor and engineer. All parties should have copies and adhere to the system finally adopted.

The inspector should locate the driving operation close to a soil boring in order to compare driving behavior to soil conditions. To facilitate this, the soil boring locations should be shown on the pile plans. If a particular plan does not cover an area in which a boring has been made, co-ordinates should be given

locating the nearest boring or borings relative to a point on the plan.

The technical specifications should be studied for the usual purpose of becoming familiar with the job. Normally, the specification will cover the general topics of actual pile construction along with other procedural matters, including (a) contractor submittals relative to the type of pile, follower (if any), and hammer that will be used, (b) load test arrangements, and (c) the sequence in which the work will be performed. All contractor submittals required by contract to be submitted prior to construction should be obtained. It is likely that additional information described later, beyond that required by contract, should also be obtained for the inspector's file prior to construction.

The contract is the source of information on pay items and measurement of pay items. Data forms used during construction should be designed to lead to an accurate count of pay items.

Soil boring data is normally part of the contract documents. However, the manner in which it is ordinarily furnished bidders is seldom useful to inspectors without additional effort. Where a small number of borings occur, it is most convenient to put all graphical logs on one piece of paper, preferably  $8\frac{1}{2} \times 11$  inches or  $11 \times 17$  inches in size. For large quantities of borings, several profiles can be constructed. The data should be plotted to scale against elevation; it need not be to scale horizontally. The boring data should be accompanied by a plan ( $8\frac{1}{2} \times 11$  inches) of the borings, showing outlines of the structures and also the designation and limits of each pile plan sheet. The plan thus becomes a useful index to the piling operation. With the soil profile in a readily usable form, the inspector can develop a feel for how the piles are penetrating relative to the soil conditions. As the job progresses, he is then in a position to detect anything unusual that might occur and can relay the information immediately to the design engineer.

On many projects a design report or design memorandum is available which describes the soil conditions and the manner in which the final design was made. The document provides relevant background information; it points out any unusual or critical features of the project to which the inspector must give extra attention. The inspector is likely to find that the soil borings have been worked into a

soil profile in the design report, thus saving him the work described above with respect to soil borings.

**Sequence of Construction.** Specifications often require the contractor to make a submittal indicating the sequence in which he proposes to perform his operations. On projects with complicated working conditions or tight schedules, the sequence may be specified for the contractor. Whether from submittals or conferences with the contractor, the inspection agency needs a knowledge of the following events:

1. Date of first driving operation and the number and types of rigs involved.
2. Schedule for startup of additional rigs.
3. Location of each rig and the order in which work will be performed with each rig.
4. The number of concreting crews to be utilized if cast-in-place piles are involved.

There are a number of sequences that can be considered typical. The rig may start up by driving indicator piles (test drives, not load test piles) at various locations on the site for purposes of verifying predictions on driving behavior and determining pile order lengths. This may be followed by driving piles for load test purposes prior to actual production. Another typical sequence involves driving one or more test piles during the earliest possible phases of production. It is also possible that no test piles or indicator piles will be required, and production driving is started without these preliminary steps. This is likely to be the case where a load test program has been completed prior to bidding.

Two major items of importance to the inspection team can be developed from a full knowledge of the planned construction sequence. First, the number of inspectors that must be available at any given time can be estimated. A guide to the quantity of personnel required can be obtained with the aid of Table 1. The required number of inspectors can be determined by summing the manpower requirements for simultaneous operations. In addition, at the start of driving at least one extra man should be available to document any unexpected occurrences. This man can be eliminated later after the driving operation has settled into a routine.

The second item of importance is that the driving of test piles and indicator piles adjacent to soil borings can be arranged. Driving records for piles adjacent to borings allow comparisons to be made

**Table 1**  
**Approximate Personnel Requirements\***

Operation	Personnel
Driving	1 man per rig.
Concreting	1 man per concreting crew for intermittent work; 2 men per concreting crew for steady work.
Pay Length	1 man can make 100-150 measurements per day.
Load Test	1 man per shift can observe up to 4 simultaneous tests.
Clerical	1 man can manipulate 200-250 pile items per day.
Supervisory	1 supervisor per 5 inspectors if inexperienced; can be 1 supervisor per 8-10 inspectors with experienced personnel.

\* Survey crew personnel requirements are not included. One man should be available at the start of driving and remain until a job routine is well established.

between design predictions and construction realities. It is desirable for this to occur as soon as possible because pile load test data is most meaningful to the designer when the borings are immediately adjacent.

**Driving Equipment.** Information on the contractor's driving rig is often required as a submittal. However, the following items of information should be in the inspectors file even if they are not required as a submittal.

1. Hammer make and model number along with the manufacturer's list of specifications giving at least: (1) weight of ram, (2) stroke, (3) speed, (4) air or steam pressure required at hammer or source, (5) hose size required, (6) boiler or air compressor size required, and (7) recommended hammer cushions. In the case of hydraulic hammers the pump requirements should be stated. (Other types of hammer are covered in the section on hammer operation).
2. Weight, dimensions and composition of the hammer cushion, drive head and pile cushion, if any. This comprises all hardware between the hammer ram point and the top of the pile. Photographs can be helpful.
3. Data on the pile cross-section used and the lengths actually furnished. Special items such as tip reinforcement and splices should be included.
4. Data on auxiliary equipment such as specifications on a jet pump, size of hose used, size of pipe used and details of the nozzle. If pre-drilling is utilized, the specifications on the drill should

be obtained giving at least power and speed; the type of auger bit should be documented and measured. Photographs of such auxiliary equipment are desirable.

5. Manufacturer's specifications for the boiler or air compressor model used should be obtained as well as the make, model and nominal capacities. Any boiler used should bear an up-to-date inspection plate.
6. Data on the crane (or other rig) such as make, model number and nominal capacity (tons). The length and width of the crawler undercarriage and width of crawler pads should be recorded. The lengths of boom and leads should be recorded as well as the distance between guide rails in the leads. Maximum in batter and out batter should be known along with the capability for side batter, if any. If the boiler or compressor is mounted behind the crane as counterweight, it should be noted.

**Data Forms.** A complete set of data forms should be available prior to construction. The forms can be of standard design with modifications made as required to suit the project. If completely new or additional forms can improve data acquisition, their implementation is encouraged. The forms of most general interest follow:

Individual Pile Driving Record  
Daily Summary of Pile Driving  
Inspection and Measurement of Piling  
Inspection of Concreting of Piling  
Piling Production Summary  
Pile Summary

Good data forms serve the useful purpose of a check list of important items to be observed. Specifics of the various data forms are covered in subsequent sections of this manual.

Unless specified, a decision must be made on the smallest units of measurement. Feet and inches to 1/8 inch are compatible with feet and hundredths; these are the smallest divisions recommended. Ordinary adding machines may be used to advantage when working with measurements to 0.01 ft. Tolerances given in the specifications should be considered before deciding on the smallest units of measurement.

**Production Day Number.** On most projects some code is adopted relating the project schedule to the calendar. Usually the contractor is required to com-



plete the project within a certain number of working days or calendar days after award of contract. A method of communication in this regard is to assign consecutive numbers to the days on the calendar referred to the contract. Thus "Production Day 1" would be the first day on which work was supposed to take place contractually. Subsequent days are numbered consecutively and include or exclude weekends and holidays depending on the contract wording. If not specified, it is recommended that all calendar days be numbered so that work performed on weekends does not disrupt the numbering system. With this technique piling progress can readily be compared to schedule. Other satisfactory systems are available for accomplishing this purpose; it is recommended that a system of some kind be employed.

**Inspector Attitude.** The inspector should concern himself with making accurate unbiased observations of all important events related to pile driving. This is especially important if driving proceeds other than as anticipated; the incidence of this is very high. If driving proceeds other than as anticipated, the inspector should not assume faulty operation on the part of the contractor; the cause might very well be unanticipated soil conditions or faulty design on the part of the engineer.

When trouble occurs one of the first questions to arise is whether or not the contractor's equipment is operating properly because the pile driving record should reflect soil conditions at the site, not a combination of soil conditions and faulty equipment operation. Whenever pile driving problems arise, speculation as to cause usually covers a wide range of topics. Elimination of potential causes can best be made on the basis of accurate data observations. Opinions unsupported by data carry much less weight.

In addition to making data observations, the inspector must also approve completion of various phases of construction and make reports on pay items and other prescribed topics. The inspector should always be aware that prompt performance of these duties is required so that follow-on work can be performed expeditiously. The contractor has both the right and the obligation contractually to perform his work as rapidly as possible. If the inspection of work takes more than a reasonable minimum of time, the contractor usually can claim extra compensation for delays caused by the inspectors.

**Pay Items.** Pay items and methods of measuring them are normally covered in complete detail in the specifications. However, where a job proceeds other than as originally planned, items of work may be required that are not covered by the specifications. In such cases the contractor will probably claim payment for the additional work. The inspection agency should be aware of all work items that may become pay items so that appropriate records are kept.

There are innumerable ways of setting out pay items in the specifications. The following is a combination checklist of pay items and list of questions, the answers to which should be known before construction begins:

1. Is there a lump sum covering a stated quantity of piles of a stated type, size, length and detail (with or without reinforcing, for example) amounting to an aggregate total footage?
2. What price is paid if the designer adds a pile to the quantity stated in Item 1? Is the aggregate footage adjusted accordingly?
3. What amount is credited if the designer deletes a pile from the quantity stated in Item 1? Is the aggregate footage adjusted accordingly?
4. What price is paid per foot for footage in excess of the aggregate footage in Item 1 adjusted for Items 2 and 3?
5. What amount is credited per foot for footage less than the aggregate footage in Item 1 adjusted for Items 2 and 3?
6. Is there a price per hour for a fully manned pile driving rig to cover delays caused by the owner (for example, out-of-sequence moves) and work items not covered in the specified pay items (for example, redrives)?
7. Is redriving a pay item or is it part of the contractor's risk?
8. How is payment handled for piles stopped short by unexpected obstructions, and for additional piles to replace the obstructed pile?
9. Are splices a pay item? Are splices in the leads treated separately from splices on the ground?
10. Is extra payment made for piles driven through overburden above cut-off elevation?
11. Is the cut-off length of a pile a pay item?
12. Is the furnish length of a pile paid for separately from the driven depth?
13. Are a specified number of load tests included in a lump sum figure?

14. How are additional load tests paid for relative to the specified number in Item 12?
15. How are deleted load tests credited relative to the specified number in Item 13?
16. Is the mobilization and demobilization of each rig paid separately as a lump sum?
17. Is predrilling, jetting or spudding included in the contractor's risk or is it paid separately per pile or per foot?
18. Does the job involve piles of different sizes and details, such as piles including reinforcing steel? Are they differentiated so that payment may be determined for varying quantities, such as Items 1-5 or some other method?

If the job proceeds other than as originally planned, the inspection agency should observe the work performed by the contractor that was not anticipated in preconstruction planning. Such work as performed by the pile driving rig is covered in diary form on the "Daily Summary of Pile Driving" described subsequently. Work performed away from the rig should be recorded in diary form listing (a) man hours by craft, (b) equipment hours, (c) material used, and (d) units of work performed.

An example of the foregoing discussion arises when piles drive deeper than anticipated and a splice is required. If the splice is performed in the leads, the work is covered on the "Daily Summary of Pile Driving." If the condition persists, the contractor may splice piles on the ground before they are supplied to the rig. The inspection agency should keep records on the splicing operation as described above. Unless splices are known to be a pay item, the contractor will probably make a claim for extra compensation. Until a final decision is made on the claim, it is necessary to have records from which a fair price for splices may be determined in the event the claim is accepted. If the inspection agency fails to keep records and a claim is accepted, the contractor's records will become the only basis for determining a fair price.

Job progress photographs are routinely made on large projects. Detailed photographs should also be obtained for all items of work not progressing as originally planned. Such items as unexcavated areas requiring driving through overburden, standing water in work areas, soil conditions requiring mats under the rig, overhead obstructions, pile damage, and any-

thing else that conceivably could be the basis for a claim should be photographed.

**Composite Piles.** Composite piles have two or more parts consisting of different types of piling. For example, the lower portion of a pile may be timber or pipe and the upper portion corrugated shell. The foregoing inspection procedures are fully adaptable to such piles. In the case of the pipe-shell combination, the furnish length of pipe and shell must be known separately because the specifications may impose restrictions on the length of the lower portion. Pay length would still be determined by inside measurement as described for cast-in-place piles. Similarly, in the case of the timber-shell combination, the furnish lengths of timber and shell must be known separately. Pay length would be the length of timber plus the inside measurement of the shell. The inspection and measurement data forms can readily be modified to accommodate composite piles.

**Material Specifications.** Material specifications usually cover the manufacture, transportation and handling of piles until they are driven. Federal guide specifications are commonly used on federal projects; their non-federal equivalents are mentioned herein for correlative purposes. After a pile is driven the material specification usually cannot be applied, especially those portions related to tolerances on size and straightness.

For example, timber piles are usually specified with reference to ASTM Designation D25 and AWWA (American Wood Preservers Association) C3 and C12 for treatment.<sup>1</sup> If 35-ft Douglas Fir piles are specified according to ASTM Designation D25-58, Class B, they will have minimum butt and tip diameters of 12 and 8 inches respectively. The specification may also state the butt and tip diameters in addition to stating Class B piles. In the event piles 40 ft or longer are actually required once driving starts, the tip diameter drops to 7 inches for Class B piles, apparently in conflict with the 8 inch minimum stated by the designer. In this case the provisions of Class B control because the situation is different (longer piles) than assumed by the designer, and the 7-inch tip is

<sup>1</sup> Book of ASTM Standards (1969), "Specifications for Round Timber Piles," ASTM Designation: D25-58; American Wood Preservers' Association Standard Specification for Pressure Treatment, AWWA C3; American Wood Preservers' Association Standard Specification for Treatment Results, AWWA C12.

acceptable. A recent revision, ASTM Designation D25-70, helps eliminate the conflict described above.

Another apparent conflict occurs when a timber pile drives shorter than anticipated and is cut off. As a result of the taper, the final in place butt diameter may be less than the 12 inches specified. This is not a real conflict because the situation is different (shorter piles) than assumed by the designer, and the smaller butt diameter is acceptable.

In both examples given above the material specification was complied with up until driving started. However, the specification could not reasonably be applied after driving.

Steel piles are usually specified under ASTM Designation A36<sup>2</sup> for H-piles and ASTM Designation A252 (Grade 1, 2 or 3) for pipe.<sup>3</sup> Precast or prestressed pile specifications usually cover manufacture, transportation, and handling in full detail; a commonly referenced specification is the AASHTO (American Association of State Highway Officials) standards for prestressed piles.<sup>4</sup>

The concrete to be used in cast-in-place piles is ordinarily described in detail by the specifications. Important characteristics of concrete have been described in the section on concreting. The only additional requirement is the normal routine concerning cylinder strengths. Concrete cylinder strengths can be adversely affected by the techniques of sampling, preparation and storage to the detriment of the contractor. The inspection agency has a duty to use good technique relative to concrete cylinders; otherwise, the contractor may have a valid claim if faulty cylinders become the basis for rejecting piles. Many agencies have specifications or manuals on making and storing cylinders; the specifications may reference one of them. In any event, good practice according to a recognized standard should be utilized.

Corrugated shells used for cast-in-place piles are often specified on a performance basis; the contractor is solely responsible for providing shells meeting specified minimum overall dimensions and having adequate strength to avoid collapse, leaks etc. Some-

times the designer specifies a minimum thickness (gage) of metal, depth and pitch of corrugation and type of seam or joint, welded or crimped. Shell splices may be welded. In the case of stepped shells, a threaded joint is common. Whether specified or not, the inspection agency should have a record of the details of the items mentioned above for possible future reference.

The inspection agency is normally responsible for collecting and filing mill certificates, wood pile treatment certificates, concrete cylinder break reports, etc. If any concrete cylinder strengths are lower than specified they should be brought to the attention of the contractor immediately so that corrective action may be started. A cylinder of low strength is not necessarily cause for pile rejection. Occasional strength values 10 to 20 percent less than specified are normally acceptable; modern specifications usually contain such a provision.

### 3 DRIVING OPERATIONS

**Stake Out.** The job specifications usually state who is responsible for stake-out. Ordinarily this service is provided by the owner or his engineers, or is made an obligation of the contractor. The normal and desirable procedure is to provide a stake at the location of each pile; the stake may be labeled with the job designation of the pile as shown on the pile numbering plan. The cut-off-elevation or some other reference mark is usually provided on each pile stake or on a separate stake adjacent to a pile group. When pile driving takes place at a given location, the inspector should be able to observe labels on a sufficient number of pile stakes so that it is at all times clear where the driving operation is located relative to the pile numbering plan.

**Pile Marks.** The job specifications usually require the contractor to mark piles by length in a manner satisfactory to the engineer. The precise method by which this is accomplished will vary from job to job. Ordinarily the piles are marked in intervals not to exceed five feet in the lower part of the pile with one foot intervals used in the upper part of the pile. If, for example, a pile is driven approximately 100 feet deep and the first 50 feet drives or pushes under the weight of the hammer then there is no need to

<sup>2</sup> Book of ASTM Standards (1970), "Specifications for Structural Steel," ASTM Designation: A36.

<sup>3</sup> Book of ASTM Standards (1970), "Specifications for Welded and Seamless Pipe," ASTM Designation A252.

<sup>4</sup> American Association of State Highway Officials Tentative Standard Specifications for Prestressed Piles.

mark the pile at less than 5 ft intervals for the first 50 feet. Thereafter, if the pile drives very easily for the next 30 ft to a total depth of 80 feet there is still no reason to use less than 5 foot intervals. However, from 80 feet until bearing is reached the pile should probably be marked in 1 foot intervals. On the other hand, a pile for which driving is required virtually full length might properly be marked at 1 foot intervals. When the pile begins to take up, the contractor's personnel should be required to mark the pile in 1 inch intervals or intervals of 0.1 feet, depending on the measuring system being used. If the pile lengths become predictable, then it is possible to have the last several feet marked in 1 inch intervals before the pile is picked up and driven.

The inspector should check on the contractor's pile measuring crew as often as necessary to insure that they are doing a conscientious job. The use of cloth measuring tapes should be banned because they have a tendency to stretch; steel tapes are recommended. Measurements should be made from the tip of the pile upwards; the total length (furnish length) should be marked at the top.

**Pile Placement.** Ordinarily the job specifications will require piles to be driven with fixed leads, that is, leads rigidly attached to the crane boom and to the horizontal member running from the crane to the bottom of the leads or spotter (other names are also used). The boom is capable of being raised or lowered, and the spotter is capable of in and out motion. Thus, it is possible to move the leads in the plane of the boom and spotter to produce a vertical or battered position. Most pile driving rigs are equipped for swinging the leads sideways; rigs must usually be especially equipped for side batters.

Most pile driving contractors insist upon a level site upon which to work the pile driving crane. With a reasonably level site it is possible to pull a pile into the leads, spot it over the position marked by the stake, and then plumb the top of the pile over the desired pile position. This process requires skill on the part of the crane operator and diligence on the part of the pile driving foreman. The foreman often uses a carpenter's level to check the plumbness of the pile.

Some job specifications require that piles be located and driven with the aid of a template. This is usually required for piles placed through water or when a number of batter piles are involved and their

location is considered to be critical. Sometimes a contractor will elect to use templates to aid his pile placing procedures. After the pile is placed on position and plumbed or battered as required driving may begin.

Some contractors prefer to cut holes in H or pipe piles to attach a pile lifting chain. Cutting holes in the piles causes a loss in net section for resisting loads, but no harm is done if the hole is in a portion of the pile to be wasted. The practice, however, is not necessary; steel clips welded to the piles will prevent the lifting chain from slipping.

**Pile Splices.** The number, type, and location of splices allowed on a pile are often detailed in the specifications. Details of the splicing procedure may be a required submittal. Two splicing conditions are generally recognized because of the great cost differential between them: (a) splices made in fabrication of the pile prior to driving (splicing on the ground), and (b) splices made during a delay in driving (splicing in the leads), involving costs of delaying virtually the entire pile driving rig and crew.

The number of splices allowed in a pile may be limited by the specifications. Where splicing is allowed, but the number is not limited, the contractor is free to splice at will. Sometimes splicing restrictions state that no piece shorter than 10 ft may be spliced into a furnished pile. This limits the number of splices, but not their location. In some cases the structural engineer may exclude splices from the upper portion of a pile by requiring that a splice shall not be closer than a certain number of feet from plan cut-off-elevation.

From a performance standpoint splices may be required to provide:

1. Full compression, tension, and bending resistance of the pile section. This type of splice should be acceptable on virtually any project.
2. Full compression and a percentage of the tension resistance of the pile section (for piles with both compression and tension loads).
3. Full compression resistance of the pile section (for piles subjected only to compression loads).

Prefabricated splice sleeves or other fabricated parts are often used to speed splicing operations, especially for splices in the leads.

INDIVIDUAL PILE DRIVING RECORD										REDRIVE (25)		REJECTED (26)	
PROJECT: LOCATION: OWNER: ENGINEER: CONTRACTOR:										PROD. DAY NO. (1) RIG NO. (2)			
(27)										DATE (8) BY (9)			
(27)										PILE DES'G. (3)			
(27)										FURNISH LENGTH (4)			
(27)										PILE X-SECT. (5)			
(27)										TIME: START (6) FINISH (7)			
DEPTH FEET	NUMBER OF BLOWS	DEPTH FEET	NUMBER OF BLOWS	DEPTH FEET	NUMBER OF BLOWS	DEPTH FEET	NUMBER OF BLOWS	DEPTH FEET	NUMBER OF BLOWS	DEPTH FEET	NUMBER OF BLOWS	DEPTH FEET	NUMBER OF BLOWS
5		35	3	65	5	95	17	125	9	155			
10		40	2	70	6	100	46	130	10	160			
15		45	3	75	7	105	104	135	13	165			
20		50	3	80	10	110	117	140	12	170			
25		55	4	85	9	115	65	145	29	175			
30		60	4	90	10	120	55	150	39	180			

Furnish length: \_\_\_\_\_  
 Cut-off elev. \_\_\_\_\_  
 Length \_\_\_\_\_  
 Tip elev. \_\_\_\_\_  
 Foreman: \_\_\_\_\_  
 Weather: \_\_\_\_\_  
 Shift: 1 2 3

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Figure 1.

Splices of precast, prestressed, and timber piles, where allowed, are usually specified in complete detail. Some concrete piles are designed to be sectional, and use proprietary splice details.

For splicing steel piles (pipe and H-sections) the specifications often require a certified welder. In some labor markets, this places an undesirable burden on the contractor. It is satisfactory if the welder can be certified only for the type of weld he is required to perform.

When a pile is spliced in the leads, or prior to a second stage driving, it is common to trim off any damaged or deformed tops in preparation for splicing. The furnish lengths and pay lengths for the lower pile section on the Individual Pile Driving Record, Daily Summary of Pile Driving, and Inspection and Measurement Forms should be adjusted accordingly.

**Pile Driving.** During the actual process of pile driving one of the inspector's duties is to satisfy himself that the hammer is operating properly. The main reason for this concern over proper operation of equipment is that driving is usually terminated when the resistance exceeds a certain number of blows per inch. In order for driving resistance to be meaningful, it is necessary that the equipment be operated consistently. A thorough discussion of pile driving hammers is given in Appendix II; the other items that are to be observed during pile driving are covered below.

During driving, the inspector's primary duty is to record the number of blows per unit of penetration; this may be per 5 foot of driving, or per foot of driving, or at the end of driving it can be in terms of blows per tenth of a foot or blows per inch. This information must be obtained at the time of driving or it is forever lost; therefore, a suitable data form for the individual pile driving record is a practical necessity.

An example of an individual pile driving record is given as Figure 1. Pertinent items on Figure 1 are identified by circled numerals which correspond to numerals in the following list of explanations:

- 1,2,3 Production Day Number, Rig Number, and Pile Designation adopted during preconstruction organization described previously.
- 4 Furnish length is the actual length of pile under the hammer. If spliced, indicate length of each piece. This length is available at the top of each pile according to the pile mark-

ing system described previously. See item 24 below concerning trimming tops of spliced piles.

- 5 X-Section is the description of the pile cross-section such as HP 12x53 for an H-pile, and 12.75" OD 0.250" for a pipe-pile. This is useful for projects where more than one pile cross-section is utilized, but may be ignored where only one cross-section is used throughout a project.
- 6 Time Start is the hour and minute when the hammer first starts driving the pile on a given day.
- 7 Time Finish is the hour and minute when the hammer strikes the last blow on a given day for a given set-up of the hammer on the pile. Redriving of a pile is treated as a complete separate drive with respect to both start and finish times.
- 8,9 No comment required.
- 10 Indicates that the pile penetrated to this depth under the static weight of the hammer.
- 11 Pile is penetrating so easily that blows are recorded for 5 ft intervals.
- 12 Pile is penetrating sufficiently slow that blows can be recorded in 1 ft intervals.
- 13 Driving was stopped at this depth at the time noted. The pile was then spliced and driving resumed at the time noted.
- 14 Final bearing is imminent and penetration is sufficiently slow that blows can be recorded in 1 in. intervals. Final depth is 147 ft-4 in.
- 15 Approximate ground elevation at location of the pile.
- 16 The final depth of penetration of the pile below ground obtained from item 14 above. Depth should be measured from ground elevation, item 15 above.
- 17 The final rate of penetration in blows per foot or blows per inch.
- 18 Hammer model. This is useful for projects where more than one hammer model is being used. Shortened designations can be used, such as "#1" for a Vulcan #1 hammer.
- 19 Blow rate is the number of hammer blows per minute. This should be recorded for firm driving when the hammer is operating essentially as it does at final bearing. The rate

should be in the range indicated by the hammer manufacturer. This should be recorded several times per day as a minimum, plus as many times as required for the inspector to develop a feel for proper hammer speed.

- 20 Boiler or compressor pressure should be recorded several times per day. The pressure should always be adequate to maintain hammer speed at final driving, and also be as recommended by the hammer manufacturer. In the case of closed top diesel hammers, bounce chamber pressure is recorded; this should be equal to that corresponding to the desired hammer energy as indicated by the hammer manufacturer. An "x" or a check mark can be used to indicate whether boiler/compressor pressure or bounce chamber pressure is being recorded. The inapplicable item, boiler or compressor, should be crossed out. For open-top diesel hammers this item can be replaced by "Observed Ram Stroke."
- 21 Remarks should cover reasons for delays, other than for splices, and any unusual or non-routine items noticed during the driving operation. Examples would be pile damage, noting drift of the pile off center after hitting an obstruction, or reasons for rejection. If a follower is used, it should be described adequately.
- 22 The depth to which drilling, jetting or spudding was performed prior to driving should be recorded. Indicate the applicable item by circling, or cross out the inapplicable items.
- 23 In some cases piles are driven through overburden above cut-off elevation. The length so driven is the difference between ground elevation and cut-off elevation.
- 24 Note the pile footage marks at which splices were made. Note remaining furnish length of pile if the head is trimmed of damaged material prior to splicing.
- 25 This item should be noted by an "x" if the record applies to redriving a pile.
- 26 This item should be noted by an "x" if the pile has been rejected. The reasons for rejection should be stated under remarks.
- 27 Information on these items should be printed at the time the form is printed.

**Final Driving Criteria.** Ordinarily specifications require that pile driving be continuous from start to finish. The reason for this is that piles often drive differently after they have penetrated part way and have been allowed to rest. The blow count per foot usually increases when a pile is allowed to set. As a consequence, a pile driven in stages will have a driving record different from a pile driven continuously. If the inspection agency is to obtain a feel for how a pile is behaving relative to the criteria, it is necessary that some uniformity in driving conditions be maintained. Where piles consist of one or more pieces, there is no choice; delays will occur at the splices. However, this process in itself will assume a pattern if the time consumed in splicing is reasonably constant. For the foregoing reasons, all test drives and test piles should be driven in the same manner and with the same equipment as production piling, including delay time for splices. Another source of delay in driving that may be unavoidable is unhooking of the pile lifting chain or rope.

The engineer will usually require the final penetration resistance to be equal to a certain number of blows per inch and that this must be observed over a distance of a certain number of inches. For example, the final resistance required might be ten blows per inch and it might be required that the last three inches of driving be at the rate of ten blows per inch or more. Another method of expressing the same criterion might be that final driving will involve thirty blows for three inches or less of penetration.

There are other methods of stating final criteria. One of these is that the piles shall be driven until a certain number of lineal feet are below ground or until the pile tip reaches or goes below a certain elevation. Other criteria involve a combination of the foregoing wherein a pile is required to penetrate to at least a certain elevation and then once the tip is below that elevation the driving resistance must equal or exceed a certain number of blows per inch.

Certain types of structures require piles that attain a certain depth regardless of the driving resistance encountered; in such cases auxiliary methods, such as jetting or predrilling, are required to obtain penetration. For most structures, however, once a pile attains a certain blow count equal to or greater than that determined acceptable, it will usually perform satisfactorily even if it did not go to the depth

indicated on the plans. On jobs where the final driving resistance is the sole criterion, it is rather unusual for the pile lengths to be the same as those given on the plans; they will usually be either longer or shorter—perhaps both. In any event, the inspector should pay special attention to the number of blows for the final inch or foot of driving.

Where tip elevation is part of the driving criteria, it should be subtracted from ground elevation to determine the required depth of driving; the required depth must be increased for batter piles to allow for the batter distance. Even in cases where tip elevation is not part of the pile driving criteria, the information is useful to the inspector for comparison with both the soil profile and the designer's expectations as to the depth to which the pile would drive. By having information available on both the ground surface elevation and the soil profile before driving, the inspector is in a position to make a check on the actual conditions immediately, and to inform his superiors if anything is other than anticipated.

**Indicator and Load Test Piles.** Both indicator and load test piles should be driven in the same manner as production piles, with the following exceptions. When driving indicator piles (test drives), it is recommended that they be driven longer than required or be driven to very high driving resistances, say 20 blows per inch maximum. The reason for so doing is to observe whether or not the pile will penetrate a significant additional length if overdriven beyond the engineer's criterion, or if the pile will penetrate only a very short distance if driven to blow counts much higher than the engineer's blow count criterion. When such driving information on indicator piles is combined with the soil profile, it provides the inspector with an indication of the support characteristics of various parts of the soil profile. Indicator piles should be driven without interruption except for splices that are also required for production piles.

Piles that are designated for load testing must be driven without interruption unless it is part of the design that driving must be interrupted for a splice. An unanticipated interruption in driving of a load test pile is reason for rejection if so indicated in the job specification.

**Determining Final Driving Resistance.** The use of load test data to determine final driving resistance is considered to be the best method available. The

engineer may, however, use a dynamic formula<sup>5</sup> or the wave equation analysis of pile driving<sup>6</sup> to determine the resistance to which the test piles are driven. On small projects the designer may elect not to load test piles and will specify the final resistance on the basis of a dynamic formula or a wave equation analysis.

There are numerous dynamic formulae based on principles described in Cummings; their validity is a controversial subject. Any formula so used will be put into the specifications by the designer, and no attempt will be made herein to describe a selection of them. The Engineering News formula is very simple and widely used, but is used herein only as an example of dynamic formulae. Any formula can be plotted as shown, for example, on Figure 2, wherein the allowable working load for the pile is plotted versus hammer blows per inch. A plot of this type is a practical convenience.

The wave equation analysis of pile driving will completely displace dynamic formulae in the near future because it has a sound theoretical basis, whereas dynamic formulae have serious theoretical deficiencies. Results of a wave equation analysis are commonly presented as a plot of ultimate load capacity ( $R_u$ ) versus hammer blows per inch. The same example considered in Figure 2 is repeated in Figure 3. Note that the plot is versus ultimate load  $R_u$  instead of allowable load  $P_a$ . (The allowable load is the ultimate load divided by a factor of safety.) Two curves are shown on Figure 3, one for a purely point bearing pile and one for a purely friction pile (see EM 1110-2-2906).

All of the dynamic formulae produce curves with a shape similar to that on Figure 2. Curves from the wave equation analysis have a similar shape, although the bend in the curve is more pronounced between blow counts of 5 and 10 blows/inch. It can readily be seen from Figure 3 that there is little to be gained from driving resistances in excess of 5 to 10 blows/inch for friction piles and 10 to 20 blows/inch for point bearing piles. If driving resistances beyond 10

<sup>5</sup> A. E. Cummings "Dynamic Pile Driving Formulas," *Journal, Boston Society of Civil Engineers*, Vol 27 (1970), pp 6-27.

<sup>6</sup> M. T. Davisson, "Design Pile Capacity," *Proceedings, Conference on Design and Installation of Pile, Foundations and Cellular Structures*, (Lehigh University, Bethlehem, 1970).



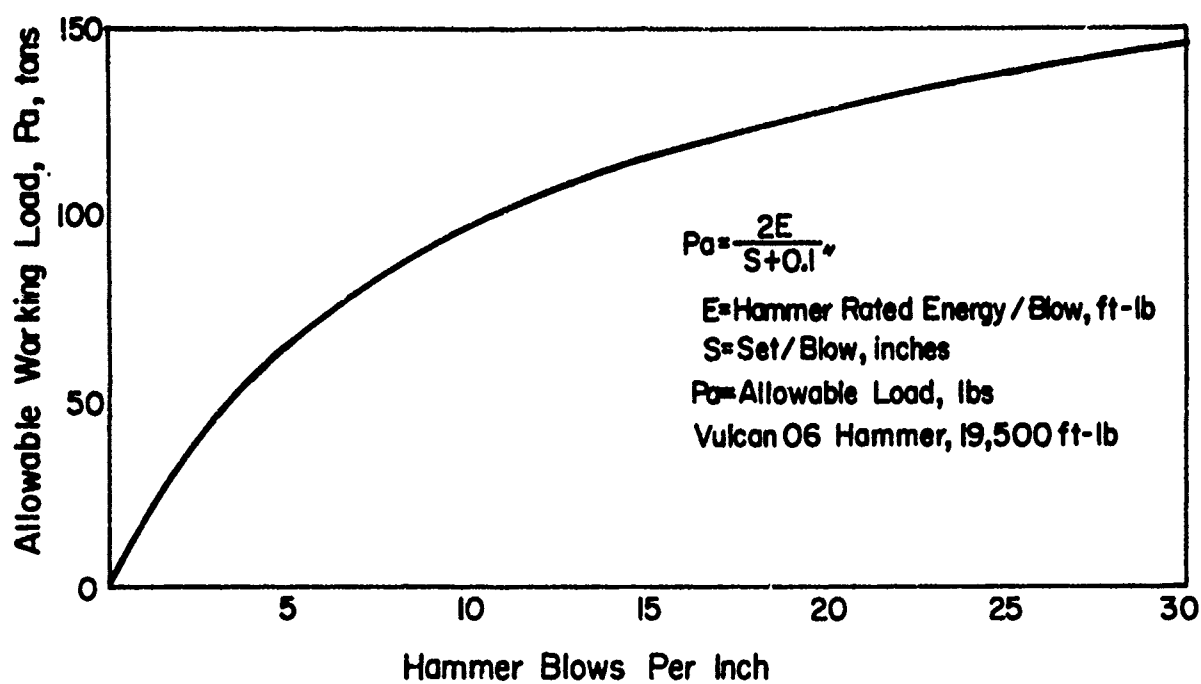


Figure 2. Engineering News Formula.

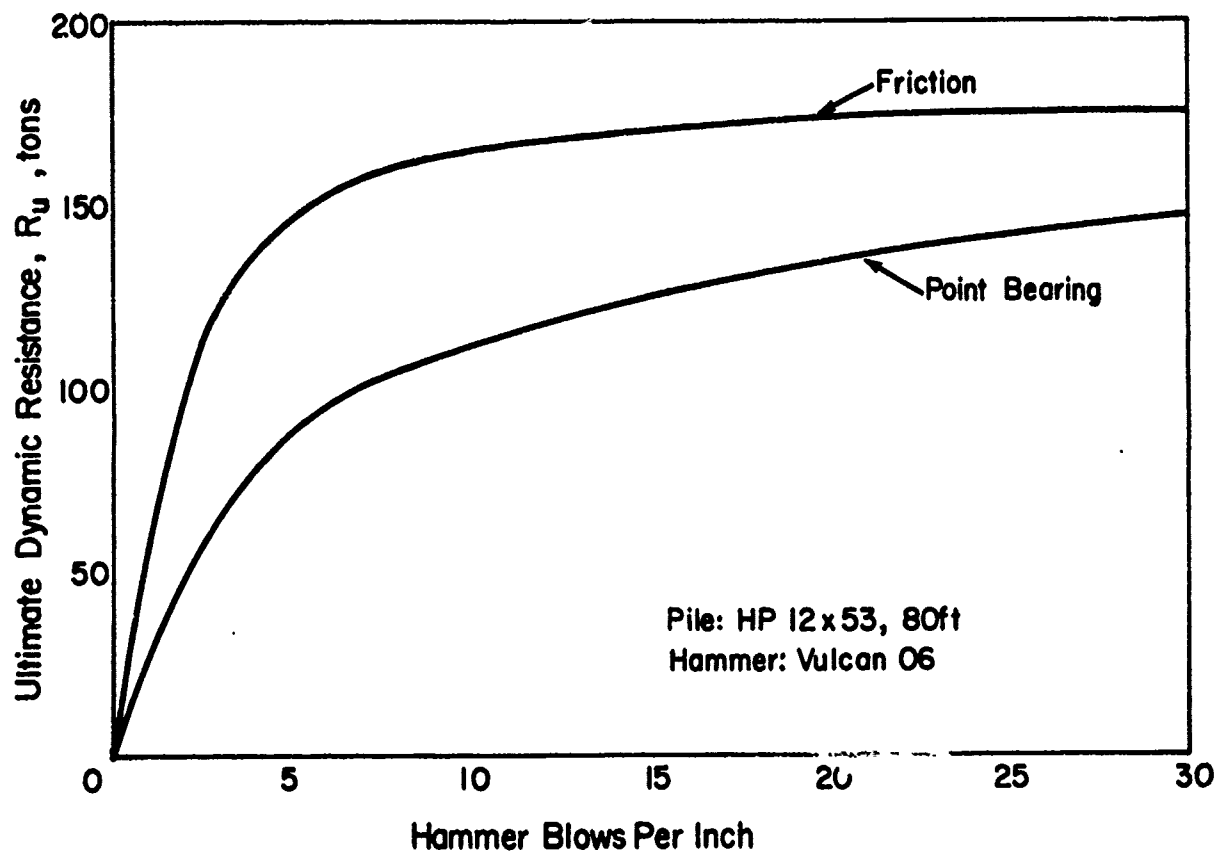


Figure 3. Wave Equation Analysis.

to 20 blows/inch are required to obtain a specified penetration, driving aids such as predrilling or jetting are desirable. Further, if the desired load capacity from a pile test is not observed within a resistance of 10 to 20 blows/inch, redesign, not an increase in required driving resistance, is indicated. An exception to the foregoing criteria is the timber pile. A reasonable upper limit is 5 blows/inch with a hammer rated at 15,000 ft-lb/blow.

Frequently a pile must be driven into a hole or through overburden below the ground upon which the driving rig is operating. If the pile is too short the hammer must extend below the bottom of the leads; lead extensions are often used for this purpose. Another common technique is to use a pile follower between the pile and the drive head. Most pile specifications prohibit followers because followers can influence the dynamic driving characteristics. Proper use of followers is a matter of design; the design engineer should review and approve the characteristics of a specific follower before it is used on the project. The wave equation analyses of pile driving is required to assess the characteristics of followers.

**Load Tests.** Pile load tests are performed generally under one or more of the conditions described below:

1. Pile driving and load testing program prior to bidding.
2. Pile driving and load testing program after award of contract, but prior to start of routine driving operations. On jobs covering a large plan area, it may be required that specified load tests be completed in a given area before routine production starts in that area; in this case all load tests on a job would not necessarily be completed prior to start of routine driving operations.
3. Pile load tests are scheduled as early as possible during the course of routine driving operations.
4. The engineer may designate for load testing a pile that has been or will be driven during routine driving operations.

In cases 1 and 2 above, the engineer is usually seeking to test his designs and to develop driving criteria for them. In cases 3 and 4, the engineer is confident about both the design and the driving criteria, but is using load tests for verification.

A load test program may also involve reaction piles and test drives or indicator piles driven at various locations on the site for purposes of verifying the designer's assumptions. If unanticipated problems are to occur on a given jobsite, the first piles driven will usually provide a preview of things to come. Therefore, it is highly desirable that the inspection agency observe carefully all test piles, reaction piles and indicator piles driven using all the techniques described previously. An apparent excess in the number of inspection personnel assigned to a project is justifiable insofar as it assures that all early data on a project are accurately recorded.

Details of the load test apparatus are usually described in detail in the specifications. In addition, a contractor submittal is usually required covering structural details and instrumentation. The specifications should also state whether the contractor performs and reports the test, or whether the contractor performs it under the inspector's directions. In the former case, it is desirable for the inspection agency to observe the test full-time, making sure that all data are recorded.

Load test specifications often incorporate a standard specification, ASTM (American Society for Testing and Materials) Designation D1143-69. However, none of the pile load test specifications in common use cover the subject of instrumentation adequately. Supplementary information that will be valuable to the inspection team is available in Davisson.<sup>7</sup>

Both the designer and the inspection agency should be aware that the performance of a pile during testing depends on whether the pile is isolated or in the middle of a cluster. A pile located in the middle of a cluster of routinely driven production piles may perform better than the same pile tested without piles immediately adjacent unless the test pile was the last pile driven. It is advisable that the test piles not be surrounded by other piles closer than allowed in the load test specification, or in ASTM Designation D1143-69.

<sup>7</sup> M. T. Davisson, "Static Measurements of Pile Behavior," *Proceedings, Conference on Design and Installation of Pile Foundations and Cellular Structures* (Lehigh University, Bethlehem, 1970).



Interpretation of load test data is the duty of the engineer unless performance criteria are given in the specifications. The ASTM specification does not give performance criteria; it covers only the method of test.

**Pile Marking and Cut-Off.** In some situations piles must be cut off immediately after driving because the pile butt interferes with driving the next pile. In such cases the pile may be rough cut above cut-off-elevation so that driving may proceed. Final cut-off takes place later. Usually, however, the driving sequence is planned so that uncut piles do not interfere with subsequent operations, and only one cut is required. In either case, the inspection procedure described herein requires that a pile footage mark be visible below the cut.

For piles that are rough cut, the inspector must insure that the pile crew places or leaves a legible footage mark below the cut. In addition, whether rough cut or not the pile designation should be placed on a sufficient number of piles so that it is possible at all times to locate the work relative to the pile numbering plan.

Steel, concrete and untreated timber piles may be marked with lumber crayon, paint sticks or a variety of other materials. Treated timber piles present a problem. Lumber crayons usually produce marks that last sufficiently long for driving purposes, but not long enough for other inspection and measurement operations. A suggested method of marking treated timber is to use cloth laundry marking tapes and an indelible marker or felt tip pen. The footage mark and pile designation are written on the tape and then tacked or nailed to the pile. It is essential that the marking materials used produce marks that will not wash off in rain or otherwise be removed by construction operations.

**Daily Summary of Pile Driving.** The individual pile driving records described previously are made under field conditions involving perhaps poor weather plus steam, air or diesel exhausts containing droplets of oil. As a consequence the individual record is often smudged, folded and the blow counts made only as legible as time permits. Further, the quantity of such individual records can be voluminous where production rates are high. A form summarizing pertinent data for each pile is desirable to cut down on the number of documents that must be handled and to provide a clean legible record.

A data form labeled "Daily Summary of Pile Driving" is presented as Figure 4; this covers the activities of one rig for one shift. The summary satisfies the requirements stated above and also provides a means of keeping a diary on the activities of each rig. Pertinent items on Figure 4 are identified by circled numerals which correspond to numerals in the following list of explanations:

- 1 Production Day Number adopted during pre-construction organization described previously.
- 2 Hammer model. Shortened designations can be used such as "#1" for the Vulcan #1 hammer.
- 3,4,5 No explanations required.
- 6 Circle the day and shift number applicable. Circle the Rig Number adopted during preconstruction organization.
- 7 Give the pile plan numbers on which the piles covered by the summary are located. This is particularly useful on large jobs where a large number of pile plans are involved.
- 8 Any remarks of a general nature applicable to the entire shift.
- 9 Time of Day is the beginning time of each activity summarized, e.g. the time driving starts on a pile, the time a delay begins, or the time a rig starts an out-of-sequence move.
- 10 The designation on the pile plan.
- 11 Furnish length is the actual length under the hammer at the end of driving. This length is available at the top of each pile according to the pile marking system described previously.
- 12 Indicate with an "x" whether boiler, compressor or bounce chamber pressure is being given.
- 13 Blow rate is the number of blows per minute that the hammer strikes. This should be recorded for firm driving when the hammer is operating essentially as it does at final bearing. The rate should be in the range indicated by the hammer manufacturer. This should be recorded several times per day as a minimum, plus as many times as required for the inspector to develop a feel for proper hammer speed.
- 14 Final penetration rate is the number of blows for the last inch of driving.
- 15 Penetrated length is the length driven below ground. This should correspond to the depth below the elevation given as item 16, below.

- 16 Approximate ground elevation at location of the pile.
- 17,18 These columns are available for special items such as: Redrive, drill, jet, spud, splice, drive through overburden, pile cross-section, and follower. Use these columns as indicated by job requirements.
- 19 Note any unusual events during driving. In particular give the reason for rejection of a pile at the time of driving.
- 20 Use an "x" to indicate that the pile was rejected at the time of driving.

In general items 9 through 20 are exactly the same as for the individual driving record, from which the data is obtained.

The summary should be kept current with the driving. Often the inspector has time between piles to transfer the required data from the individual record to the summary. When time is short the inspector must at least enter the time at which driving started on the last pile and the pile designation; the summary can be completed later.

When a rig is driving on a routine basis, it is assumed that the time period between two consecutive piles on the summary is consumed driving the first pile and moving in sequence to set up over the second pile ready to start driving. Whenever this routine is broken, the time of day must be noted on the summary and the entire line, plus additional lines if required, must be used to explain the reason for interruption of the routine. Typical reasons for interruption are equipment repairs and servicing, and weather; specifics should be given, such as "repair boiler" or "repair hammer." Out of sequence moves must be timed because they may be pay items or basis for a claim; the reason for moving out of sequence should be noted. The inspector must be diligent in keeping the summary form current in order for it to function effectively as a diary.

It is possible to inspect a job wherein a routine has been established using the summary form alone; of course the blow count record is lost. On the other hand, it is neither convenient nor proper to use only the individual records without the summary because a systematic method of keeping a diary on the activities of each rig would be lost or would have to be developed separately.

Upon completion of the summary form the inspector has completed his duties with respect to the driving operation.

#### 4 INSPECTION AND MEASUREMENT

**Purpose and Scope.** After piles have been driven it is the duty of the inspector to determine their acceptability and to make or verify measurements of contract pay items. In many cases inspection and measurement can be performed by survey personnel alone. In other cases survey personnel and inspection personnel can work simultaneously or in sequence to obtain the required data.

Measurement is often one of the problem areas in the organization and management of a pile driving operation. There may be several pay items for each pile that is driven; when the number of pay items is multiplied by the number of piles on a large project, the scope of the bookkeeping operation can be appreciated. A systematic procedure coupled with comprehensive data forms is mandatory on large projects if the job is to be performed efficiently and properly. Several comprehensive data forms have been developed and are presented herein with explanations to illustrate the items that may have to be covered in the inspection and measurement operation. The forms actually used for a given project should be redesigned using the included forms as a guide. An important consideration is that the redesign of forms be thought through to the end of pile inspection and verification of final pay items so that no routine matters are overlooked.

Inspection personnel must work closely with the contractor in inspection of driven piles. After driving the piles must be marked for cut-off. If the owner's engineers or agents are responsible for marking, they must perform their job as closely behind the driving operation as possible. Then, the piles must be inspected prior to concreting in the case of cast-in-place piles, and prior to follow-on work in the case of solid pile cross-sections.

Contractors often wish to complete their work as closely behind the driving operation as possible. The inspection team has a duty to co-operate in scheduling inspection work in order to allow the contractor to proceed expeditiously. At the same

time the contractor has an obligation, usually a contractual matter, to permit proper inspection. Most conflicts in this area revolve around the matter of delays caused by the inspection team, especially with respect to approval of piles for concreting. A proper amount of time between driving and approval for concreting is hard to define because it depends largely on job conditions; one working day is suggested as a guide.

**Marking Cut-Off.** The inspection procedures given in this manual depend to a large extent on marks placed on the piles both before and after driving, and when cut-off is marked. It is essential that a system of marking be established and rigidly adhered to throughout the project. The marking system described herein is usable under a wide variety of job conditions. However, it is recognized that other systems can be superior in some situations. If another system is adopted, its effects on the total system of inspection should be considered to assure its adequacy.

A template for making a standard mark is illustrated on Figure 5(a). The template can be made of metal and curved as required to fit round piles. The handle (not shown) should hold the upper and lower portions together. Lumber crayon, paint sticks or other reasonably permanent markers can be used to produce the mark shown in Figure 5(b). The upper line is the cut-off mark, and may be obliterated in the cutting process. However, the arrow and lower lines remain after cutting. The lower line is made 2 to 6 inches below the cut line depending on the space available on a given project; however, the distance is standardized for each project.

The survey party marking cut-offs should produce the mark on Figure 5(b). In addition, a pile footage mark as placed before driving should be legible below cut-off sufficiently removed from the cut line so that it will not be obliterated. If the only legible footage marks would be lost by cutting, it is the surveyors duty to transfer a footing mark below cut-off. It is suggested that the transferred footage mark be placed at the lower line made from the template. The survey party should also be responsible for marking a sufficient number of piles with their job designation so that any pile in the vicinity can be located on the pile numbering plan.

Treated timber piles present a special problem because lumber crayon or other markers do not

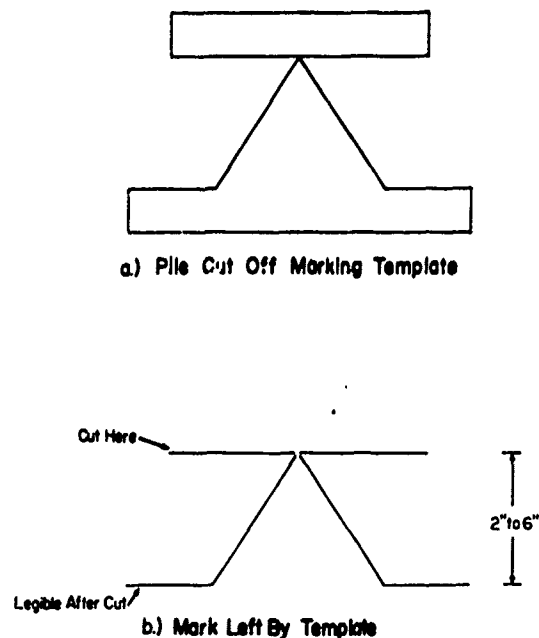


Figure 5. Pile Marking Template.

provide a sufficiently permanent mark. A suggested method is to use three nails or tacks on the arrow mark of Figure 5(b). One nail is at the tip of the arrow on the cut line, whereas the other two nails are on the lower line at the shoulders of the arrow. Pile footage marks and pile designations can be written on cloth laundry marking tape with indelible markers, as described for marking of timber piles at the end of driving. The tape is then tacked to the pile at the appropriate location below cut-off.

Where the tops of piles have been driven below cut-off-elevation, but are within tolerance, the mark on Figure 5(b) can still be applied. The furnish length of the pile should still be visible as a footage mark reference. For piles driven so far below cut-off-elevation that the marker will not reach cut-off, it is necessary to place the mark low and indicate the distance up to the cut-off-elevation. Usually the mark would be placed some whole number of feet below cut-off, such as 1 or 2 feet. In addition to pile designation and a legible footage mark, the number of feet to cut-off is marked. Where the pile butt is too close to the ground surface for convenient marking it should be treated as a special case, using a stake or other method of indicating the required information.



Other piles are driven through overburden above cut-off elevation, and the cut-off-elevation is inaccessible. The cut-off mark is then placed some whole number of feet above cut-off-elevation. In addition to pile designation and a legible footage mark, the number of feet to cut-off is marked. Standing water and other site conditions at the time the survey crew does their work sometimes make it necessary to mark piles above cut-off.

**Solid Cross-Sections.** Timber, pre-cast concrete, H-piles, and other solid structural sections are piles that cannot be inspected internally without special provisions. As a consequence the inspector can observe only the pile cut-off-elevation and the location relative to those specified on the plans. These items coupled with damage at the head of a pile represent the total of routine observations. The specifications sometimes provide for withdrawal of piles to check for damage, but this is not a routine operation. Complete notes should be kept regarding pulled piles.

If a pile is designated to be withdrawn and is found to be damaged, the specifications usually require the contractor to furnish a new acceptable pile and to redrive it at that location without compensation. Pile damage on the embedded portions of piles is almost exclusively a function of latent ground conditions and the type of pile specified by the engineer. Only in rare cases is the contractor physically at fault for pile damage below ground. However, the pile specifications usually ask the contractor to assume this risk; the contractor presumably has allowed for this in his bid. If a significant percentage of piles on a project are pulled and found to be unacceptably damaged, the cause is likely to be unexpected soil conditions or faulty design; in either case the design should be modified. The inspector should not assume that the contractor is doing a bad job if the embedded portion of a pulled pile is found to be damaged.

A data form labeled "Inspection and Measurement of Piling—Solid Cross-Sections" is presented as Figure 6. The form is designed to be utilized by a survey crew, by a pile inspector working with a survey crew, or by an inspector alone subsequent to the work of a survey crew. Further, it can be utilized even after the contractor has cut-off the piles. Information for columns 1 through 6 must be obtained in the field, whereas the remaining information can be entered in the office.

Pertinent items on Figure 6 are identified by circled numerals which correspond to numerals in the following list of explanations:

- 1,3 No explanation required.
- 2 Number of sheets on a particular day.
- 4 Information on these items should be printed at the time the form is printed.
- 5 Give the pile plan numbers on which the piles inspected are located. This is useful for large jobs where a large number of pile plans are involved.
- 6 Any remarks of a general nature applicable to the entire page.
- 7 Useful for totaling the pay items on a page, and cumulatively for a number of pages.
- 8 Useful for filing inspection forms by consecutive number throughout the job.

All data columns bear numbers, and explanations are given below according to column numbers:

- 1 Pile designation adopted in preconstruction planning (should be available from the top of several piles in the field with the remaining piles easily identified from the pile plan).
- 2 Design cut-off-elevation available from the pile plan, abbreviated C.O.E.
- 3 Marked elevation is the elevation at which the cut-off mark was placed. Ordinarily this is the plan cut-off-elevation, but for short piles the mark would be below plan C.O.E., and for piles driven through overburden it would be above plan C.O.E.
- 4 The algebraic difference between marked elevation and the plan C.O.E. For piles marked high the difference is positive, and should equal the cut footage indicated by the surveyor. For piles marked low the difference is negative, and should equal the fill figure indicated by the surveyor. Ordinarily Column 4 is zero because marked elevation equals plan C.O.E.
- 5 The pile foot mark showing below the cut mark.
- 6 The distance from the pile foot mark in Column 5 up to plan C.O.E. or the marked elevation. If the pile foot mark happens to be at the lower line on the cut mark, the distance up to C.O.E. is the standardized distance between the lower line and the cut line on the marking template.



- 7 Pay length is defined as the length below plan C.O.E. It is equal to Column 5 plus Column 6 minus Column 4. If Column 4 is negative or bracketed, Column 7 equals Column 5 plus Column 6 plus Column 4, numerically. This column and all subsequent columns may be completed in the office.
- 8 Tip elevation is plan C.O.E. minus pay length, or Column 2 minus Column 7.
- 9 Furnish length is obtained from the daily summary of pile driving or the individual pile driving records. This may be a pay item.
- 10 Cut-off length ordinarily is defined as furnish length minus pay length or Column 9 minus Column 7. If a pile is driven through overburden and the length in the overburden is a pay item, the cut-off length becomes Column 9 minus Column 7 minus Column 12 (explained below). This may be a pay item.
- 11 Ground elevation at driving may be obtained from the daily summary of pile driving or the individual pile driving records. This may also be obtained by the surveyors at the time of marking the pile.
- 12 Length through overburden is defined as ground elevation at the time of driving minus plan C.O.E., or Column 11 minus Column 2. This is of interest when it is a pay item. Where a follower is used a decision will have to be made on payment; the actual pile remaining above plan C.O.E. may be paid separate from the footage driven through overburden. If such is the case the observed data must allow separation of these quantities.
- 13 Splices may be a pay item. The number in a given pile may be obtained from the individual pile driving records or the daily summary of pile driving.
- 14 Insert an "x" if the pile is rejected.
- 15 Insert extra columns as required to indicate depth of jetting, predrilling or spudding, or items such as final penetration resistance and re-driving.
- 16 Remarks must include reasons for any rejections.

For small jobs covering a short period of time, it is possible to use Figure 6 as a summary of the job giving final pay quantities. It is only necessary additionally to check the pile designations against a

master list of all pile designations used on the job to be sure all piles are driven and that the list is complete without duplication.

On large jobs where interim progress payments are to be made, the job summary and final pay quantities should be determined in a different manner, as explained subsequently. However, the inspection sheets (Figure 6) completed within the period of time covered by the progress payment can be used to determine pay quantities applicable to that period.

**Pile Tolerances.** The specifications for some projects require an as-built survey showing the actual plan locations of each pile head and the actual cut-off elevations. The engineer then determines the acceptability of each pile or each pile cluster on the basis of this information. The information to be furnished is obtained by surveying crews and should be collected from them by the pile inspection team.

On many projects the engineer merely specifies that piles shall be located within two to six inches of the specified plan location. Tolerances on the order of 2 to 3 inches are common and reasonable except that the tolerance for timber should be larger, say 3 to 6 inches. Timber piles should have longer tolerances because they are inherently crooked and out-of-round. Any pile falling within the specified range with respect to plan location is considered acceptable and the inspection record need show nothing more than a check mark indicating that the pile was satisfactory. The specifications may or may not give a tolerance on cut-off-elevation. The requirements of the job with respect to the manner in which the pile caps and reinforcing steel connect to the piles will determine the tolerance. However, in most cases a tolerance of one-inch up or down is reasonable.

Pile cut-offs within a tolerance of one inch are easily within a contractor's capabilities. However, the plan location specification of pile heads may be very difficult for contractors to meet even within the normal tolerances. If cobbles, boulders, or other obstructions are present especially near the ground surface there is a tendency for a pile to shift direction out of alignment and plan location. There is very little that a contractor can do except to be diligent in trying to obtain plan location at the end of driving. If the pile driving foreman has been diligent in his effort, he has done all that the state

of the art permits. Under these conditions, piles that are deemed to be out of location are a function of ground conditions. However, the specifications usually require the contractor to correct this at his expense, and the risk is presumably covered by the contractor's bid price.

Determination of pile damage requires some judgement because the process of hammering on a structural material will always produce some alteration to it, some of which is acceptable and some not acceptable. Acceptable and unacceptable damage to timber piles is usually described in pile specifications. On concrete and steel sections the requirement should be that the pile appear to be structurally sound. Some aid to judgment is required in this respect, and questions should be referred to the structural engineer.

As-built surveys and other checks on tolerances must be completed promptly while the contractor is still on the site and has access to the work.

**Cast-in-Place Piles.** Piles that are to be filled with concrete after they are driven present an opportunity for internal inspection that solid pile cross-sections exclude. The pile concreting operation itself must be inspected because very seldom is a pile adequate without a good concrete core. Cast-in-place piles consisting of a corrugated shell filled with concrete depend for their adequacy solely on the concrete core. The importance of a proper concreting operation can not be overemphasized.

The inspection of cast-in-place piling will proceed first with internal and external observations on the pile to determine its acceptability for concreting. The survey crew must complete its work of marking cut-off elevations on the pile and other marks as described previously, and the contractor should have cut off the shells. Where the portions of the pile to be cut off are short enough that internal inspection can still be managed, it is possible to inspect ahead of the contractor's cutting operation.

A data form labeled "Inspection and Measurement of Piling-Cast-in-Place" is presented as Figure 7. The form is designed to be used by an inspector after the piles have been marked and cut off. The information for columns 1 through 6 must be obtained in the field, whereas the remaining information is obtained in the office. Pertinent items on Figure 7 are identified by circled numerals which

correspond to numerals in the following list of explanations.

- 1,3 No explanation required.
- 2 Number of sheets on a particular day.
- 4 Information on these items should be printed when the form is printed.
- 5 Give the pile plan numbers on which the piles inspected are located. This is useful for large jobs where a large number of pile plans are involved.
- 6 Any remarks of a general nature applicable to the entire page.
- 7 Useful for totaling the pay items on a page, and cumulatively for a number of pages.
- 8 Useful for filing inspection forms by consecutive number throughout the job.

All data columns bear numbers, and explanations are given below according to column numbers:

- 1 Pile designation adopted in preconstruction planning. Should be available from the top of several piles in the field with the remaining piles easily identified from the pile plan.
- 2 The pile foot mark showing below the cut mark.
- 3 Measured distance from the pile foot mark (Column 2) to the top of the shell.
- 4 Total exterior footage is the length from the pile tip to the top, and is equal to Column 2 plus Column 3.
- 5 Inside length is the measured interior depth of the pile. To this must be added the thickness of the closure plate at the tip. (A tape can be weighted and modified at its zero end so that the measurement automatically allows for the plate thickness.) Column 5 should equal Column 4 for pipe, but may be larger for corrugated shells; further explanations are given later.
- 6 This item allows for actual cut-offs not being exactly at plan C.O.E. (cut-off-elevation). Using the lower line on the cut-off mark as a reference, plan C.O.E. can be reconstructed with a short ruler. If the pile top is low the distance up to plan C.O.E. is positive. If the pile top is high the distance down to plan C.O.E. is negative and should be bracketed. All subsequent columns may be completed in the office. Note that shells may be cut either low or high because of overburden, water, etc. The distance



- cut or fill marked by the survey must be included in such cases.
- 7 Pay length is the algebraic sum of Column 5 plus Column 6. If Column 6 is negative or bracketed, Pay Length is Column 5 minus Column 6 numerically.
  - 8 Furnish length is obtained from the daily summary of pile driving or the individual pile driving records. This may be a pay item.
  - 9 Cut-off length ordinarily is defined as furnish length minus pay length or Column 8 minus Column 7. If a pile is driven through overburden and the length in overburden is a pay item, the cut-off length becomes Column 8 minus Column 7 minus Column 13 (explained below). This may be a pay item.
  - 10 Design cut-off-elevation available from the plan, abbreviated C.O.E.
  - 11 Tip elevation is plan C.O.E. minus pay length, or Column 10 minus Column 7.
  - 12 Ground elevation at driving may be obtained from the daily summary of pile driving or the individual pile driving records. This may also be obtained by the surveyors at the time of marking the pile.
  - 13 Length through overburden is defined as ground elevation at the time of driving minus plan C.O.E., or Column 12 minus Column 10. This may be a pay item.
  - 14 Splices may be a pay item. The number in a given pile may be obtained from the individual pile driving records or the daily summary of pile driving.
  - 15 Insert an "x" if the pile is rejected.
  - 16 Insert extra columns as required to indicate depth of jetting, predrilling or spudding, or such items as final penetration resistance and redriving.
  - 17 Remarks must include reasons for any rejections.

For small jobs covering a short period of time, it is possible to use Figure 7 as a summary of the job giving final pay quantities. However, it is necessary to check the pile designations against a master list of all pile designations used on the job to be sure all piles are driven and that the list is complete without duplication. Further, the data form "Inspection of Concreting of Piling," Figure 8, must be checked similarly against a master list to be sure all

piles are concreted before the final pay quantities can be accepted.

On large jobs where progress payments are to be made covering a period of time, the job summary and final pay quantities should be determined in a different manner to be explained subsequently. However, the inspection sheets (Figure 7) can be used to determine pay quantities applicable to that period. The concrete inspection forms will have to be checked against the inspection forms or a master list to be sure all piles on the inspection forms are complete.

The possibility of inspecting cast-in-place piles internally is technically an advantage over solid pile cross-sections. There are several features of internal inspection that need amplification. The most obvious item is external length versus internal length plus plate thickness. For pipe piles these measurements should check easily within an inch. In the case of corrugated shells, it is possible that the shell can stretch vertically during driving and the internal measurement may be longer than indicated by the exterior marks. The difference between the two measurements is an indication of stretch in the shell. The difference between inside and outside measurements is particularly important if the inside measurement is more than an inch less than the outside measurement. If a pile collapses, it becomes impossible for the weight on the end of the measuring tape to reach the pile tip. This causes the internal measurement to be shorter than the external and is a good indication of the depth at which problems have occurred.

Along with the measurement, the inside of the pile should be inspected visually with the aid of sunlight and a reflecting mirror or a high powered spot light. Either of the foregoing techniques is equally or more satisfactory than that of lowering a light into the pile. A very restrictive specification requires that the entire pile tip can be visible and free of debris and water. Less restrictive specifications sometimes state that at least half of the pile tip must be visible, or that some portion of it must be visible. In many ground conditions these restrictions are entirely too conservative.

For piles containing water, a weighted measuring tape can be used to get a measure of the amount of water in the bottom of the shell. If soil clings to the tape weight, it indicates one into which debris or soil has penetrated. It is possible



for a pile tip to be both dry and out of sight and for the inside and outside measurements to check satisfactorily; piles of this type will normally prove to be acceptable if they are load tested, even though they would be rejected under the specifications.

When water, soil, or debris is present, it is necessary that the debris and soil be cleaned out and that the water be drawn down to an acceptable depth before the pile can be accepted for concreting. Piles containing water, soil or debris should automatically be rejected until they can be cleaned out and shown to contain less than an acceptable amount of water at the time of concreting. An acceptable amount of water may be defined in the specifications, or the specifications might state that the pile must be clean and dry. If more specific directions are not available, it is usually satisfactory if the pile contains no more than two inches of water at the time of concreting. Acceptable concrete can be obtained in a pile by competent contractors with up to six inches of water at the tip. However, a pile with more than six inches of water at the time of concreting should be rejected.

Collapse of pipe and shell is another item often covered in pile specifications. Collapses not decreasing the pile cross-section by more than a certain percentage are often judged acceptable. Allowances up to a 25% decrease in the pile cross-sectional area are reasonable as long as the pile can be taped from bottom to top.

An additional item that can be observed for cast-in-place piles is plumbness. Specifications usually state that piles shall be within a batter of 0.25 inches per foot, or 2 percent of their length. The inspector can make a quick check to see if the pile is within the plumbness allowance by letting the weight on the pile measuring tape act as a plumb bob, and determining the location of the top of the tape when the bob is resting against the side of the pile at some known depth. In questionable cases, more precise methods may have to be adopted; this should be done in conjunction with the structural engineer and should be considered as a special operation. Another good method of checking a pile for plumbness is to drop a pebble into the pile from the center and to observe whether or not the pebble strikes the side before it strikes the bottom. If the pebble strikes the side below an acceptable depth, then the plumbness is satisfactory.

In reality, the plumbness tolerance given in most specifications is too restrictive for fully embedded piles. Piles that are partially embedded are more critical structurally, and are often placed with the use of templates. Therefore, for fully embedded piles a tolerance of 5 to 10 percent of the length might be fully acceptable on many projects. It should be noted that if the deviation from plumb is very great, it is possible to drive one pile into a previously driven pile, thus perhaps causing both piles to be rejected. For this reason, diligence on the part of the pile driving foreman is required in maintaining plumbness. However, there are many ground conditions where diligent workmanship on the part of the pile crew will still lead to piles exceeding the plumbness tolerance. Again, this is a risk that the contractor usually accepts and presumably covers in his bid price. Assuming diligence by the contractor, if out-of-plumbness leads to a significant number of rejects, then it is probable that the plumbness tolerance is too restrictive or that the design is badly conceived.

**Concreting of Piles.** On projects where a contractor's concreting crew can be kept busy full time, it is possible to pour enough concrete that two inspectors must be assigned to the operation. One inspector would keep notes, whereas the other would perform tests. On projects involving an intermittent concreting operation, it is possible for one man to perform all of the functions.

Piles that have been accepted during the inspection process previously described may be concreted. However, there is another inspection immediately prior to placing the concrete to guard against the possibility of water, soil and debris entering the pile after the first inspection. Further, piles that may have been rejected during the first inspection may have been cleaned by the contractor, and must be inspected again just before placing the concrete.

A data form labeled "Inspection of Concreting of Piling" is presented as Figure 8. Important items on Figure 8 are noted by circled numerals that correspond to the numerals in the following list of explanations:

- 1.3 No explanation required.
- 2 The number of sheets on a given day by a given concrete inspection crew.
- 4 Concrete inspection crew number. Useful on large jobs where more than one concrete inspection crew is working.

- 5 These items should be printed at the time the form is printed.
- 6 Indicate the pile plan numbers on which the piles being inspected are located. Useful on large jobs with a large number of pile plans.
- 7 General remarks applicable to the entire page.
- 8 Useful for filing by consecutive number throughout the job.
- 9 The form is designed to operate in batch units of concrete such as one truck load. The supplier's ticket should be collected by the inspector and the ticket number entered on the form.
- 10 The number of cubic yards indicated on the supplier's ticket.
- 11 The time of day at which water was added to the mix. This should show on the supplier's ticket.
- 12 The time of day when concrete is placed in a given pile.
- 13 Concrete slump measurement.
- 14 Number of cylinders taken from each batch of concrete.
- 15 Ambient air temperature.
- 16 Temperature of the concrete as placed.
- 17 Date when the piles were inspected and measured using the form on Figure 6 "Inspection and Measurement of Piling—Cast-in-Place."
- 18 Pile designation from the pile numbering plan. Should be visible at the top of several piles with other piles easily identified from the pile plan.
- 19 Can be used to indicate completed pile has been checked against a master list of piles.
- 20 Measured length of pile from Column 5 of Figure 6 for piles cut at plan C.O.E. For piles originally cut at other than plan C.O.E. check to be sure that a second cut has not been made. If in doubt, or if a second cut has been made, measure the inside length of the shell.
- 21 The remaining portion of a batch of concrete may be insufficient to fill the pile under consideration. Also, piles driven through overburden may be concreted only up to plan C.O.E. In such cases the length of pile shell unfilled must be measured.
- 22 For partially filled shells determine the length actually placed by subtracting the length unplaced from the full length (Column 20 minus Column 21). For piles of uniform cross-section the length placed should be summed for a given batch of concrete.
- 23 For piles of uniform cross-section the yardage indicated on the supplier's ticket should fill a known total length of piling. This theoretical length should be placed opposite the summation of actual length placed with the batch of concrete under consideration. See Item 22 above. The numbers should be approximately equal. In the case of tapered piles or piles of non-uniform cross-section, the word "length" should be crossed out of Item 23. Then a table of yardage versus length measured from the tip applicable to the non-uniform pile under consideration is used to determine the theoretical yardage for each pile. The yardages are summed for the piles concreted from a given batch of concrete and compared to the yardage indicated on the supplier's ticket, Item 10. The yardages should be approximately equal. When a new batch of concrete is used to complete a partially filled pile of non-uniform cross-section, the theoretical yardage used from the new batch is determined by subtracting the theoretical yardage previously placed (Item 23) from the theoretical yardage for the entire pile.
- 24 Remarks must include the reasons for any rejections. Note depth of water in the pile.
- 25 Place an "x" in the column if a pile is rejected at the time of concreting.

The inspection team should have an agreement, possibly in the contract, with the contractor regarding timely notification of intention to pour concrete in given areas. It is essential that the inspection team know which piles are to be poured so that they can obtain copies of the Inspection and Measurement data forms applicable to those piles; this is essential for Items 17 and 20 covered above.

For piles previously accepted for concreting, the additional inspection required before concrete placement may be only visual where the pile tip can be observed. It is only necessary to be sure that water, soil and debris have not collected in the pile. Where

water can be seen in the pile, or when the tip cannot be observed, the pile should be retaped and determinations made on whether or not soil and debris have entered the pile and whether or not the depth of water at the tip is acceptable.

For piles previously rejected, but allegedly corrected by the contractor, the data form on Figure 7 "Inspection and Measurement of Piling—Cast-in-Place" should be completed. The remarks column should indicate that this is a reinspection of a previously rejected pile. If it is satisfactory, concrete may be placed.

The foregoing inspection procedure will not work if the contractor is allowed to pour simultaneously from more than one truck or one batch of concrete. Simultaneous pouring should not be permitted.

**Concreting Problems.** Structurally sound in-place concrete is essential for a satisfactory pile. The designer usually provides fairly complete specifications for pile concrete. Many of the topics discussed below may be covered by the specification, but others may have been omitted. Generally acceptable pile concreting practice is described to provide the inspector with background information, and to aid his judgement on matters left for his decision.

At the beginning of a concreting operation on a project, it will often be found that the concrete supplier is providing less concrete than shown on the delivery ticket (See Item 23 under the discussion of Figure 8). The contractor should be informed of this immediately so that he can initiate corrective measures; this is actually a favor to the contractor because he is paying for more concrete than is delivered. Sometimes the corrective measures lead to the concrete supplier providing somewhat more concrete than shown on the delivery ticket to eliminate further complaints. This is also to be discouraged because if the actual length of piling concreted from a given batch of concrete exceeds the theoretical length, then there is reason to suspect that a void has been built into the concreted portion of the pile. In such cases, it is known that one or more of the several piles concreted from a given batch or truck load of concrete may be defective. When this event occurs, those piles concreted with the questionable batch of concrete should be rejected, at least temporarily, and the contractor given an opportunity to take corrective action with his concrete supplier or the piles, whichever is at fault. A check of yield can reveal

whether the supplier is at fault. After the concrete supplier achieves a stable routine, then there should be constant and predictable small differences in the yardage indicated on the supplier's ticket and the yardage theoretically required by the piles. If the differences become large or erratic, then periodic checks of yield should be made in order to keep the concrete supplier under control.

Concrete to be placed in piles should generally have a slump of not less than 3 inches nor greater than 6 inches. The range of 3 to 5 inches is preferable for vertical piles. Aggregate size should not exceed 3/4 inch generally, with an absolute maximum of one inch.

Several job conditions can hamper concrete placing operations. A vertical pipe is the easiest type of pile in which to place concrete. It is desired that the concrete enter the center of the pipe and fall directly to the bottom with as little contact with the sides as possible. It is also necessary that no big lumps of any kind be included that could cause clogging of the pipe and perhaps create voids in the concrete core. A satisfactory method of placement involves a funnel placed on top of the pile with an outlet having a diameter at least two inches less than that of the pile. The length of the funnel inside the pile is not critical; an elephant trunk is not intended. The funnel is directed down the axis of the pile and serves as a restriction through which all concrete entering the pile must pass. If a lump or some other object plugs the funnel then it should be removed and not allowed to pass into the pile.

Concreting of corrugated shells requires somewhat more care than concreting a smooth pipe. Concrete aggregate hitting corrugations during a fall will ricochet considerably more than in a smooth pipe and it is possible for the aggregate to separate from the cement. For this reason, higher slump concretes and richer mixes are more desirable. Slumps on the order of 5 inches may be required for stepped corrugated shells, whereas somewhat less slump could be used with corrugated shells of uniform cross-section.

The worst problem that can be encountered in pile concreting is a battered, stepped, corrugated shell with reinforcing steel. For such cases a slump of 6 inches may be required along with a maximum of 3/4 inch aggregate. Further the pile should be rodged, especially in the upper 15 feet.



When placing concrete in a pile containing water in the bottom, it is desirable that the initial several lineal feet of concrete in the pile be placed as rapidly as possible. A rapid pour provides more concrete through which the water in the pile will be distributed. If the pile were concreted slowly the water would be distributed through only the lower one to two feet and the additional water might cause unsatisfactory concrete strength at the pile tip. Further, the weight of concrete poured subsequently can cause bleeding and loss of cement.

Air-entrained concrete has no advantages for cast-in-place piles if workability is otherwise sufficient. Its use is optional.

Specifications often restrict the distance of pile driving from concrete less than a certain age; minimum distances of 10 to 50 ft are common. Unless specified it is satisfactory if one open pile remains between the driving operation and a concreted pile, or if the minimum distance is 20 ft, whichever is less.

All piles must be protected from extreme heat or cold. In hot weather, the exposed concrete at the pile butt should be covered to prevent rapid loss of moisture. This moisture is essential for the proper curing of the concrete in all kinds of weather.

In cold weather, heated concrete should be used. In addition, it is necessary to protect any exposed concrete by means of salt-hay, tarpaulins, etc. In extremely cold weather, salamanders, steam (or air) heaters or steam lines may be needed to protect the piles from freezing. Note that if the pile extends above the ground surface, it is necessary to protect all of the exposed portion of the pile, not just the top surface of the pile.

The rate of strength gain for concrete is reduced when it is exposed to cold temperatures. For example, at or near freezing temperatures, early strengths are less than one-quarter of normal and the concrete is exposed to danger of frost damage. The use of Type III cement (Hi-Early) will provide a faster strength gain and thus reduce the exposure of the concrete to damage as well as reduce the time required for protection. If, for example, the temperature is kept at 40°, the time required for Hi-Early to gain service strength is about one-quarter the time required by regular cement. Calcium chloride added to the concrete will hasten the setting time and thus reduce the exposure to frost damage. This admixture

must be carefully controlled to prevent permanent damage to the concrete.

For winter concreting, it is advisable to consult the local weather bureau for current information on expected day and night temperatures and plan accordingly. Unless specified differently, concrete should not be placed at less than 40°F. Also, the minimum temperature recommended for protected concrete is 40°F.

Three or four days after pouring, pile butts should be inspected for frost damage. If any damage is noted the damaged portions must be removed and replaced.

Under the following conditions, unreinforced concrete piles could be damaged by lateral movements during construction activities:

1. Piles that extend above ground surface around which fill is to be placed.
2. Piles driven in areas to be excavated.
3. Piles in soft ground adjacent to ramps, roads or other paths travelled by construction equipment.
4. Piles immediately adjacent to deep excavations where earth movements could occur.

If any of the above conditions exist, precautionary measures such as installation of reinforcement, erection of barricades or use of tie-backs are advisable.

**Reinforcing Steel.** The addition of a reinforcing steel cage in a pile presents an obstruction. The design of the cage should take into account the concreting operation and allow proper room for it. With a reinforcing steel cage the maximum size aggregate should not exceed 3/4 inch. A high slump is usually required for concrete to flow around the reinforcing steel and fill the annular space between the cage and the pile wall. The upper 5 to 15 feet of such a pile should ordinarily be vibrated. Vibration is not required in ordinary cast-in-place piles not containing reinforcing steel. However, the upper several feet of the pile should be rodded.

In piles containing reinforcing steel it is neither practical nor necessary to vibrate below a depth of 15 feet. The reason for this is that the pressure of the concrete coupled with a proper mix and a high slump will cause the concrete to flow around the reinforcing steel as desired. It is only in the upper portion of piles that the pressure is low enough that vibration is required. Vibration to a depth of 5 feet is

ordinarily satisfactory with a proper concrete mix design; vibration to a depth of 15 feet may be required for large amounts of steel and low concrete slumps. Single dowels require only rodding, not vibration. The inspector should refer to the job specifications on concrete placement in piles for the actual requirements.

Long reinforcing bars and all reinforcing cages should have "spiders" or other spacers to hold the reinforcing cage in its design location. This is especially important for batter piles. The make-up of the cage and the spacers also must allow the concrete to pass to lower unreinforced portions of the pile. Another method of placing concrete below a cage is to pour the concrete up to the depth the cage will extend and then install the cage.

**Pile Heave.** The driving of a pile may cause an adjacent pile to move upwards; this is known as "pile heave." Point bearing piles on rock may have their load capacities seriously impaired by heave, whereas heave may cause no reduction whatsoever in the load capacity of a purely friction pile. The primary cause of pile heave is the nature of the soil profile; heave is influenced strongly by pile type and pile spacing. Both predrilling and adjustments in the sequence of driving can be utilized to alleviate the heave problem. The type of pile and pile spacing are matters of design, whereas soil conditions are an inherent job site condition.

Although pile heave is usually not caused by the contractor, in the specifications he is often required to assume the risk and to redrive heaved piles at his expense. Presumably this risk is covered in the bid price. Other methods of dealing with heave are to pay the contractor an hourly rate for redriving heaved piles, or to pay him a lump sum for each pile redriven. The specifications should state how this item will be paid; if unspecified, the contractor will probably claim an hourly rate. Redriving of piles should be recorded on individual records and the daily summaries.

Heave is usually detected by measuring the top elevation of solid piles and pipe piles as driving progresses. For corrugated shells the possibility of shell stretch introduces unknowns into the measurement of top elevations. "Tell tales," consisting of a piece of pipe resting on the tip closure plate, are not affected by shell stretch; their top elevations can be observed, thus providing a measure of pile heave.

Usually the specifications require piles to be redriven if the heave exceeds a stated amount, such as 1/4 to 1/2 inch. Precision in measuring pile heave must be consistent with the maximum heave allowance.

The final driving criteria for redriven piles may be stated in a variety of ways. From a technical standpoint, the as-furnished pile should be satisfactory when the penetration resistance (blows per inch) equals that for the original driving. However, the specifications may require the pile to be driven until the tip reaches the original depth as a minimum, or driven a stated minimum distance regardless of the penetration resistance encountered.

It should be recognized that a difference exists in the driving characteristics of piles after shortening them by cut-off, and after filling cast-in-place piles with concrete. The designer can determine if changes in the final driving criteria should be made by performing a wave equation analysis of pile driving; he can also determine what additional pile cushioning may be necessary to prevent damage to concreted piles. Both shortening a pile and filling a pipe pile with concrete will lower the number of blows per inch required to achieve the desired load capacity. However, an increase in the number of blows per inch would be required for concreted corrugated shells because the concrete is not as effective as the mandrel originally used to drive the shell. If the mandrel is reinserted in an empty shell, the original criterion is applicable.

**Rejected Piles.** The rejection of a pile is a serious financial matter to the contractor not only because of the cost of repair or replacement of the rejected piles, but also because more than one pile may be required for replacement. In addition, the contractor may have to pay for redesign of pile caps to accommodate the pile group as it is finally constituted.

A rejected pile is cause for discussion between the contractor and the inspection agency to decide if repair will be attempted or if the pile is to be abandoned. If the rejected pile is abandoned, it retains its original plan designation. However, replacement piles will bear the same designation, but with letter designations at the end. Thus, if pile 245 is rejected, and two piles are required to replace it, the replacements are designated 245A and 245B. If pile 245 is rejected, but the contractor pulls it, the replacement is still designated 245A.

[illegible]

The location of replacement piles is decided by the structural engineer. Prior to construction, the inspection agency should obtain instructions from the structural engineer on the location of replacement piles for as many conditions of pile rejection as can be imagined. Corrections should be made promptly because access to rejected pile locations may become difficult or virtually impossible. Lack of promptness in providing instructions to the contractor can be a legitimate basis for a claim by the contractor. If the corrections determined prior to construction do not apply to a given situation, the decision on corrective measures should be obtained from the structural engineer by telephone as soon as possible. The inspection records should include an as-built plan sketch showing location of replacement piles.

A corrective measure commonly proposed for rejected cast-in-place piles is to drive a pipe or a corrugated shell inside the rejected pile. This procedure can be satisfactory when the rejection is caused by water and/or soil in the open pile and the replacement can be driven through the bottom of the rejected pile. If the rejection was caused by collapse, the replacement pile would encounter damaged metal below its tip forming a soft spring and preventing the attainment of proper load capacity.<sup>8</sup> Therefore, driving inside a rejected pile is satisfactory only where the replacement pile drives through the tip of the rejected pile without forcing any part of the rejected shell wall ahead of the replacement pile tip.

Job specifications frequently require abandoned cast-in-place piles to be filled with concrete. Filling with sand or waste concrete is a satisfactory procedure in the absence of specification requirements.

The method of payment for rejected piles is seldom detailed in the specifications. In the absence of a specified method the theory of non-payment for the rejected pile itself may be applied; payment should be made for the replacement pile. If more than one replacement pile is involved, payment should be made for the average pay length of the replacement piles.

Overdriving may lead to pile damage, which in turn leads to pile rejection, especially in the case of timber piles. The designer can determine by use of

the wave equation analysis of pile driving<sup>9</sup> whether or not the hammer-pile-soil combination being used is satisfactory within the limits of the final driving criterion selected for the job. Piles that are rejected because of overdriving required by the engineer or inspector beyond the minimum requirement of the final driving criterion will probably become the basis for a claim by the contractor.

**Pile Driving Summaries.** Inspection, measurement and concreting of piles essentially completes the construction inspection activity in the field. The remaining duties of the inspection team are primarily clerical. It is necessary to summarize pile construction records for the following reasons:

1. To verify that no piles have been omitted.
2. To verify that all rejected piles are satisfactorily replaced.
3. To verify that no duplications exist in the records.
4. To determine final pay quantities.
5. To verify progress payment quantities.
6. To provide a day by day record of piling production for comparison to the job schedule.
7. To provide periodic reports on piling production for comparison to the job schedule and to show areas cleared for follow-on work.

For purposes of keeping a day by day record of piling production, the data form on Figure 9 labeled "Piling Production Summary" has been developed. Pertinent items on the form are identified by circled numerals which correspond to numerals in the following list of explanations:

- 1 Information on these items should be printed when the form is printed.
- 2 Production Day Number adopted during preconstruction organization described previously.
- 3 Date corresponding to the Production Day Number.
- 4 Indicate the number of piles driven by Rig 1 (designation adopted for rig in preconstruction organization) for the day. Do likewise for the other rigs on the job. The number of piles driven includes rejected piles.

<sup>8</sup> M. T. Davisson, "Design Pile Capacity."

<sup>9</sup> M. T. Davisson, "Design Pile Capacity."

Figure 10.

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- 5 Sum total of piles driven by all rigs for the day.
- 6 Sum total of all piles driven by all rigs through this date.
- 7 For cast-in-place piling indicate the total number of piles concreted for the day.
- 8 Indicate the total number of piles concreted through this date.
- 9 Remarks include reasons for no work (e.g. weather, or strikes) and other items of interest.

Where more than one shift is employed, as many lines may be used for a given day as there are shifts working. Where piles are driven in stages involving separate set-ups over the pile (not spliced in the leads), the columns indicated by circled numerals 4 through 8 on Figure 9 should be divided into as many columns as there are stages.

Periodically a summary may be required showing areas in which piling has been completed. This can be useful for planning follow-on work such as pile caps. A summary of this type can be made using the small scale plan described in the section on preconstruction organization. Cross-hatching may be used to indicate areas completed subsequent to the last report, and double cross-hatching to show areas completed prior to the last report.

In the discussions on inspection and measurement of piles, it was stated that the data forms on Figures 4 through 7 may be used to summarize small jobs, especially those covering a short span of time where progress payments are not involved. However, when a job covers a period of time beyond one or two progress payments, or involves piles consisting of two or more stages, the use of a summary form is virtually mandatory.

A data form labeled "Pile Summary" is presented as Figure 10. It is intended that this form be modified and simplified as appropriate for the job conditions encountered. The form is intended for listing piles in numerical order according to pile designation within category as to pile type, size and detail. The list can be made during preconstruction planning; it will serve as a checklist of work to be performed. Pertinent items on the form are identified by circled numerals which correspond to numerals in the following list of explanations:

- 1,2,3 A decision must be made by the inspection team regarding the categories of piling that can most conveniently be sum-

marized. The summary must provide accurate totals for each pay item. Ordinarily, the pay items are differentiated by pile type, pile size and pile detail (e.g. the reinforcing detail); the categories finally selected are placed in the appropriate spaces.

- 4 Use to indicate the pile plan numbers on which the piles listed on the page can be found.
- 5 A decision must be made by the inspection team as to whether this should be the total number of sheets for a given category, or the total for the job.
- 6,7 No explanation required.
- 8 Information on these items should be printed when the form is printed.
- 9 General remarks applicable to the entire page.
- 10 Pile designation adopted in preconstruction planning. List numerically.
- 11 Date pile is driven. Obtain from "Daily Summary of Pile Driving."
- 12 Page number (lower right corner) of "Inspection and Measurement of Piling" form.
- 13,14,15 Obtain from "Inspection and Measurement of Piling" form.
- 16 Page number (lower right corner) of "Inspection of Concreting of Piling" form.
- 17,18 Obtain from "Inspection of Concreting of Piling" form.
- 19-26 Repeat items 11 through 18 for the second stage of a two-stage cast-in-place pile. If three or more stages are driven, use a second line for each pile.
- 27 Total pay length for piles driven in stages. The sum of items 15 and 23.
- 28 Plan C.O.E. is obtained from the pile plan.
- 29 Tip elevation is defined as plan C.O.E. minus pay length. For single stage piles this is obtained from the "Inspection and Measurement of Piling" form.
- 30,31,32 Obtain from "Inspection and Measurement of Piling" form.
- 33 Place an "x" in the column if the pile was redriven.

- 34 Can be used to indicate date of redriving, or other information desired.
- 35 Place an "x" in the column if the pile was rejected.
- 36 Can be used to indicate invoice date or estimate date on which payment was claimed for this pile.
- 37 Design extra columns as needed to summarize data on items such as on predrilling, jetting and spudding. Be sure to have columns covering all pay items.
- 38 Remarks must include reason for rejection of a pile.
- 39 Useful for totaling the pay items on a page, and cumulatively for a number of pages.

Spliced piles of solid cross-section may be summarized on a smaller form consisting of the general headings plus columns labeled with circled numerals 10-15, 19-23 and 27-38. One-piece piles of any type may be summarized on an even smaller form consisting of the general headings plus columns labeled with circled numerals 10-18 and 28-38.

As the data forms "Daily Summary of Pile Driving," "Inspection and Measurement of Piling" and "Inspection of Concreting of Piling" are received by the inspection team's clerk, the pertinent data should be entered on the "Pile Summary," Figure 10. With this procedure errors, omissions and duplications become evident, and can be checked against the

original data sources. Note that the reference columns, circled numerals 11, 12, 16, 20, 24 and 34, provide page numbers for the pertinent data forms.

Piles added by the owner during construction can be listed in the summary at the end of the lists for each type, size, and detail. Piles deleted by the owner can simply be crossed off the list. Replacement piles should be summarized on a separate list; they may be listed as they are driven.

All routine specified pay items plus any additional pay items agreed upon during construction should be summarized in the "Pile Summary," Figure 10. Load tests do not involve a large number of items and are easily listed separately. The "Daily Summary of Pile Driving" forms should be used to develop a list of rig-hours devoted to (a) delays caused by the owner, (b) out-of-sequence moves caused by the owner, (c) redriving if not a specified pay item, and (d) any other activity by the rig for which a pay item is specified or a claim pending, or potentially pending. The diary mentioned in the discussion of pay items should be summarized to provide factual data on work items for which the contractor may make claims.

The summaries described herein will indicate that all piles have been properly installed or otherwise accounted for, and will provide an accurate count of pay items. Further, an accurate count of items for which payment may be claimed will also be available to serve as a factual basis for negotiation.

## APPENDIX I

### PILE DRIVING HAMMER OPERATION

#### INTRODUCTION

In most areas of construction activity the tools used by a contractor to perform his work are neither subjected to close inspection nor specified in detail in the job specifications. The adequacy of the work is either apparent or is determined by a test independent of the construction method. Pile driving, however, is relatively unusual in that the number of hammer blows per inch of penetration is commonly used to determine the adequacy of a pile. Thus, an impact tool designed to drive piles is used by engineers as a measuring instrument—a purpose for which it was not designed. The engineer, unfortunately, has no practical alternative; thus, he commonly is restrictive in the specifications with regard to minimum hammer size, etc.

If a pile driving hammer is to be used as a measuring instrument, it must be operated in a consistent manner in order to obtain uniform results. The only practical standard of performance is the hammer manufacturer's recommendations. Therefore, the inspector must learn enough about hammer operation to know if the hammer is being operated as recommended by the manufacturer; this procedure can help eliminate faulty hammer operation by an inattentive contractor.

There are situations where a contractor finds it to his advantage to overdrive a pile, or to underdrive it. Manipulation of the hammer controls is a method of accomplishing overdriving or underdriving. If the inspector insists on proper hammer operation, the only other method of hammer manipulation available is mechanical modification. If a contractor is sufficiently determined to manipulate hammer operation that he makes internal mechanical modifications, the procedures given herein will not prevent him from doing so. In order to prevent such manipulation the inspector would need to check all hammer parts against the manufacturer's machine drawings; this checking process is considered beyond the scope of this document.

#### HAMMER RATINGS

Hammers are normally rated in terms of their gross energy (ft-lb) per blow. For a drop hammer the rated energy is the ram weight  $W$  multiplied by the drop height  $H$ . The actual energy at impact is less than rated energy because of friction in the leads or ram guides. Energy at impact is a function of ram velocity; in order to know the actual energy at impact the velocity at impact,  $v_o$ , must be measured. Energy at impact is often estimated by applying an efficiency factor to gross rated energy. The efficiency,  $e_f$ , is defined as energy at impact divided by gross rated energy. Efficiencies of 70 percent are common.

Drop hammers are seldom used because they are too slow to be economical. Single-acting hammers were developed to increase hammer blow rate, and thus, productivity. The essential principle of the single acting hammer is shown on Figure 11(a). Steam or air pressure operates on the underside of a

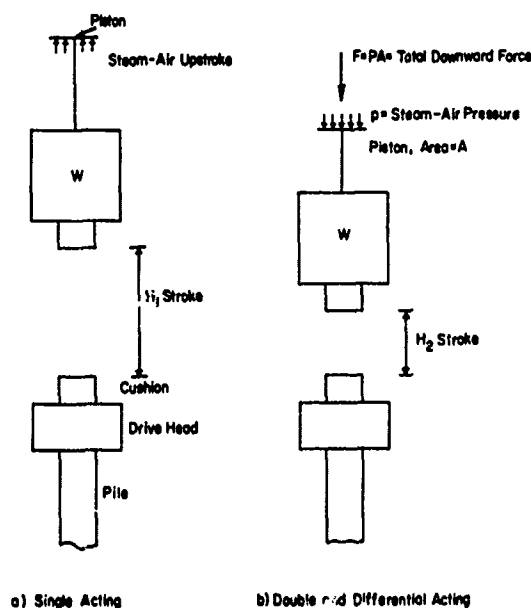


Figure 11. Steam-Air Hammers.



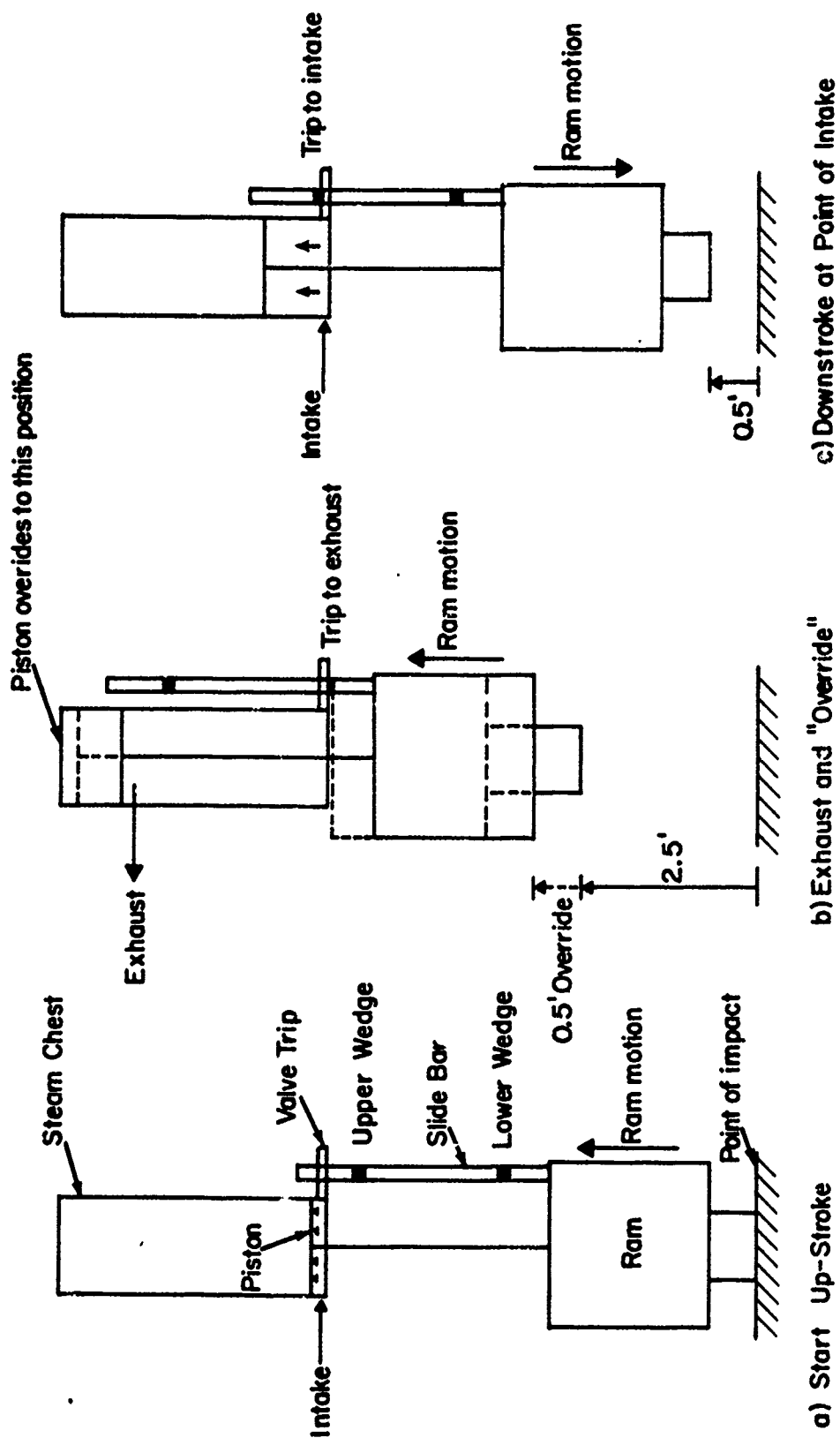


Figure 12. Single Acting Hammer.

piston to raise the ram to the top of its stroke. At the top of the stroke steam (or air) is exhausted and the ram falls through its stroke  $H$ . Single-acting hammers are rated in the same manner as drop hammers, namely,  $WH_1$  (Figure 11a).

Double and differential-acting hammers were developed to increase hammer blow rates above those for single-acting hammers. This is accomplished by raising the ram in the same manner as for single-acting hammers, but also using steam or air to force the ram downwards (Figure 11b). The downwards force  $F$  is the steam or air pressure  $p$  multiplied by the effective area  $A$ . Rated energy then becomes  $WH_2 + FH_2$ , where  $H_2$  is the actual stroke.

Double and differential-acting hammers are commonly manufactured with the same ram weights  $W$  and rated energies as single-acting models. Under these conditions, the stroke of double and differential-acting hammers  $H_2$  is approximately one-half that for the equivalent single-acting hammer  $H_1$ . Higher blow rates are achieved because of the shorter stroke.

Recently hydraulic differential-acting hammers have been developed that are equivalent to the steam or air powered models. Also, diesel hammers are rapidly displacing steam and air hammers; they are more complicated and will be discussed in more detail later.

Efficiencies of 70 percent are common for single-acting and double or differential-acting hammers.

## HAMMER MANUFACTURER'S DATA

The inspection agency should obtain the manufacturer's data on the hammers to be used by the contractor, especially the operation and maintenance manual. The technical data given therein is reliable with two exceptions:

1. Specified boiler or compressor sizes should be increased 10 to 15 percent to allow for non-ideal conditions.
2. Hammer efficiencies are overstated; claim of 80 to 100 percent are made, whereas 70 percent is more reasonable.

A typical flow diagram for steam-air hammers is given on Figure 12. Manufacturer's specifications usually give the steam-air pressure required at the

hammer; to allow for line losses, the pressure at the boiler or compressor must be maintained 20–30 psi higher. The specifications will also state the minimum hose size; any pipe used should be at least one size larger than the recommended hose size. A normal configuration with the boiler or compressor mounted behind the crane might involve up to 70 ft of pipe and 50 ft of hose. Longer lengths should involve larger sizes of pipe and hose or higher boiler-compressor pressures.

On rigs with the boiler or compressor mounted behind the crane, the supply pipe ordinarily runs by the crane operator. Two valves are located by the crane operator; one is a throttle valve whereas the other is a quick-action on-off valve. Thus, the crane operator can start and stop the hammer, and can regulate the steam-air pressure at the hammer.

Steam-air pulsations caused by hammer valve action, plus the remoteness of the hammer, make it impractical to measure pressure at the hammer. A much more reliable way of determining performance is available and will be explained later. In any event, the boiler-compressor must be capable of maintaining 20–30 psi above that required at the hammer while the hammer is operating properly.

## SINGLE-ACTING HAMMERS

The general operating characteristics of single-acting hammers will be illustrated by reference to a particular hammer, the Vulcan #1. Pertinent specifications are:

Ram Weight:	5000 lb
Energy Rating:	15,000 ft-lb
Stroke:	3 ft
Blow Rate at Final Drive:	60 blows/min.
Pressure at Hammer:	80 psi
Boiler Size:	40 hp nominal 81 hp ASME
Air Compressor Size:	565 CFM (adiabatic)
Hose Size:	2 in.

According to the preceding discussion, a boiler of 50 hp nominal size would be required, or an air compressor of 600 to 650 cfm capacity. Hose should be of 2-in. size with pipe runs 2 in. or larger. Pressure at the boiler-compressor should be 100–110 psi while the hammer is operating properly. In soft driving the

hammer may operate at approximately 55 blows/min., but should reach 60 blows/min. at final driving. The stroke should be a full 3 ft at final driving.

Mechanically the hammer goes through the steps described on Figure 12. The upper wedge on the slide bar causes the valve trip to position itself so that steam (or air) is admitted under the piston, thus causing the ram to rise. The maximum steam force is approximately twice the weight of the ram and causes the ram to accelerate upwards. Approximately 2.5 ft up on the stroke the lower wedge on the slide bar engages the valve trip, shutting off the steam supply and exhausting steam from below the piston. The ram ascends the remaining 0.5 ft to the top of its stroke by "overriding" past the exhaust point due to the upward acceleration remaining from the steam force.

The ram falls through its 3 ft stroke by gravity. However at approximately 0.5 ft from the bottom, the upper wedge engages the valve trip and admits steam under the piston. Thus, the steam valve is positioned for returning the ram to the top of its stroke before the ram impacts, but does not have sufficient time to interfere with the downward travel of the ram prior to impact.

The foregoing discussion of the mechanical action of a single-acting hammer provides background for the following statements:

1. The operator should not let the steam pressure become so high that the hammer overrides excessively on the upstroke. This will cause the ram to impact the steam chest and lift the hammer off the pile; this is also known as dancing, or racking. Such operation is destructive to the hammer.
2. It is possible for the hammer to fall through less than a 3 ft stroke if the pressure is too low to cause the required amount of override.
3. It is possible to short-stroke a hammer by using a short-stroke slide bar, with the distance between the upper and lower wedges made less than standard.
4. On the downstroke the hammer should impact at the proper distance after the upper wedge engages the valve trip. If the ram point engages the cushion too high (caused by too great a cushion thickness) the hammer is short-stroking. If the ram-point impacts the cushion too low, the hammer is overstroking and the ram may strike the

hammer base, which is destructive to the hammer.

The inspector can readily observe hammer speed and stroke when operating under final driving conditions. However, the manufacturer's operation and maintenance manuals must be consulted in order to check on the location of the impact point relative to valve operation. Thus, three important items must be checked to be sure that the hammer is operating properly: (a) stroke, (b) speed, and (c) position of the wedge and valve trip at impact.

After a hammer has been checked out according to the preceding discussion, its routine proper operation can be assured very easily. By opening the throttle valve slightly, it should be possible to cause the hammer to lift because of excessive upward override of the ram. The throttle valve should then be closed until the lifting does not exceed 1/4 inch. Proper operation of the hammer is just at the point of lifting.

The following list of problems and remedies may prove helpful if proper operation of single-acting steam (air) hammers is not observed:

1. Hammer runs too slow.
  - A. Steam pressure too low.
  - B. Piston packing too tight, most common fault. Remedy, loosen packing nuts until only hand tight, then lock nuts in place. Small amount of steam or water leak not objectionable.
  - C. Steam hose restricted in some manner. Check by trying a new hose. If hammer picks up speed, this indicates inside lining of hose has partially come loose or is torn.
  - D. Piping partially plugged. See that pipe sizes and fitting sizes have not been reduced from those recommended from boiler to hammer, and that all foreign material is out of line.
  - E. Valve in steam line broken or not opening enough.
  - F. Engineer using steam for unnecessary purposes while hammer is driving. (Example, washing down rig with steam, letting boiler run too low on water before injecting.)
  - G. Piston rings leaking excessively. Try by allowing enough steam to enter cylinder to hold ram in about half-raised position, and

note whether excessive steam is emitting from auxiliary exhaust.

- H. Hammer not receiving enough oil. Remedy, keep oil in oiler provided at all times, and if driving batter piles pay close attention to column oiling.
  - I. Slide bar guide worn badly, thereby letting bar-to-trip distance increase. This causes restriction on the valve openings. (Note: Bar being bent out can cause short stroking. Remedy, replace slide bar and pad.)
  - J. Worn trips or slide bar wedges will cause hammer to be sluggish. Remedy, replace trips or slide bar or both.
2. Hammer runs too fast, indicated by upward excessive bouncing of entire hammer when ram is on up stroke.
    - A. Too much steam on hard driving. Remedy, close throttle valve partially.
  3. Little or no bottom exhaust, and the hammer runs fast. (Hammer will probably not be striking a full blow, but this is hard to determine.)
    - A. Hammer is probably cushioning on steam caused by a twisted valve stem. Disassemble valve, inspect valve stem, and check valve setting.
  4. Little or no top exhaust, but hammer runs fast with short stroke.
    - A. Lower slide bar wedge probably in wrong position. You may have a "short stroke" slide bar.
  5. Hammer changes speeds while operating.
    - A. Boiler not large enough or not fired efficiently enough to supply hammer and engine at same time.
    - B. Boiler feed water let drop to too low a level before replenishing, thereby making boiler heat too much cold water at a time.
    - C. Inside of hose torn or loose, allowing constriction at times.
    - D. Lubrication: not oiled often enough, allowing hammer to run dry part of the time, thereby losing speed and when oiled picking up speed.
    - E. Ram holes for column badly worn, thereby allowing slide bar to move in and out against striking points of trip.

6. Hammer leaks steam at main exhaust continuously.

- A. Broken valve or badly scored valve. Remedy, hammer should be sent to shop for repair.

7. Hammer leaks steam at auxiliary exhaust during entire up stroke.

- A. Piston rings are worn out or cylinder is badly scored.

## DIFFERENTIAL AND DOUBLE ACTING HAMMERS

The general operating characteristics of differential and double-acting hammers will be illustrated by reference to a particular differential hammer, the Vulcan 50C. Pertinent specifications are:

Ram Weight:	5000 lb
Energy Rating:	15,000 ft-lb
Stroke:	15 1/2 in.
Blow Rate at Final Drive:	105-115 blows/min.
Pressure at Hammer:	120 psi
Boiler Size:	60 hp nominal
Air Compressor Size:	880 CFM (adiabatic)
Hose Size:	2 in.

According to a preceding discussion a boiler of 70 hp nominal size would be required. However, an air compressor of 1000 CFM capacity would not operate this hammer properly unless it could produce at least 140 psi pressure. The boiler would have to maintain 140-150 psi while the hammer is operating properly. Hose should be of 2 in. size with pipe runs 2 in. or larger. In soft driving the hammer may run 5 blows/min. slower than the specified range, but should run in the specified range at final driving.

Mechanical operation of the hammer appears reversed from that for single-acting hammers in that exhaust of steam from the top of the piston occurs just before the ram impacts the cushion. Further, the lower wedge throws the valve to intake steam, whereas the upper wedge throws the valve to exhaust. The inspector can readily observe hammer speed and stroke when operating under final driving conditions, but the manufacturer's operation and maintenance manual must be consulted in order to check on location of the impact point relative to valve operation. As with single-acting hammers, three important

items must be checked to be sure the hammer is operating properly: (a) stroke, (b) speed, and (c) position of the wedge and valve trip at impact.

Position of the wedge and valve trip is more critical for differential and double-acting hammers than for single-acting hammers. For this reason the cushion block materials used are usually those providing maximum stability of thickness over a long period of time. Aluminum and micarta discs are usually used, whereas wood blocks are common for single-acting hammers.

After a differential or double-acting hammer has been checked out according to the preceding discussion, its routine proper operation can be assured very easily. By opening the throttle valve slightly it should be possible to cause the hammer to lift because of excessive upward override of the ram. The throttle valve should then be closed until the lifting does not exceed 1/4 inch. Proper operation of the hammer is just at the point of lifting. The hammer is not operating properly unless it can be made to lift under final driving conditions.

The list of problems and remedies given for single-acting hammers applies generally to differential and double-acting hammers.

## DIESEL HAMMERS

**History.** Diesel pile driving hammers have been in use for many years, especially since World War II. In the early period of their development they gained a reputation for erratic and unreliable performance because of stalling and variability of the ram stroke. There are, however, many advantages to diesel hammers, and most of the disadvantages have been eliminated by recent improvements in hammer design. Many contractors now prefer diesel hammers for reasons of performance, economy, reliability, self-contained operation, rapid mobilization, cold weather starting, and low crane-capacity requirements. Because of these features, diesel hammers appear destined to become the most commonly used type of pile hammer.

Despite the advantages of diesel hammers, many engineers refuse to approve their use. This attitude arises, in most cases, out of traditional suspicion of the diesel hammer and ignorance of its real perform-

ance capability. Housel provides an exposé of the general lack of knowledge among engineers regarding pile hammers.<sup>10</sup> One of the major questions raised by engineers is how the energy rating for diesel hammers should be determined.

**Mechanical Operation.** The mechanical operation of a diesel hammer will be described with the aid of Figure 13, starting with the ram at the top of its stroke:

1. The ram descends closing the intake port and compressing a charge of air in the combustion chamber.
2. When the ram is about to impact the anvil fuel oil is injected and:
  - A. The combustion chamber pressures are sufficient to prevent impact and start the ram upwards (characteristic of soft driving), or
  - B. The ram impacts the anvil in spite of the combustion chamber pressures, rebounds and is forced upwards (characteristic of hard driving).
3. As the ram rises past the intake-exhaust port, exhaust takes place.
4. After exhaust and elimination of the force causing the ram to rise, the ram overrides upward to the top of its stroke.
  - A. In open-top diesels the stroke may be up to 8 ft.
  - B. In closed-top diesels a charge of air is trapped which functions as a spring and shortens the hammer stroke.
5. After the ram reaches the top of its stroke:
  - A. The ram falls by gravity for open-top diesels.
  - B. The ram falls by gravity aided by the spring force from the bounce chamber.
6. The cycle repeats.

Open-top diesel hammers are analogous to single-acting steam hammers, whereas closed-top diesels are analogous to differential and double-acting hammers in that the stroke is shortened and the ram forced downwards in order to obtain higher blow rates. An

<sup>10</sup> W. S. Housel, "Michigan Study of Pile Driving Hammers," *Proceedings, ASCE*, Vol 91, No. SM5 (September 1965) pp 37-64.

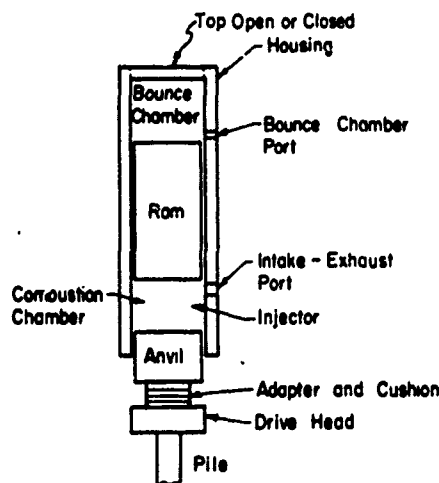


Figure 13. Schematic of Diesel Hammer.

important distinction to be made is that the bounce chamber force is fully reliable, whereas the downwards steam force in a steam hammer is variable. Bounce chamber pressure is usually measured and, by the laws of physics, related to the ram stroke that would have occurred if the top were open instead of closed.

**Efficiency.** Diesel hammers have been shown to be efficient tools; in fact, their efficiency is approximately 100 percent compared to 70 percent for steam hammers.<sup>11</sup> Efficiency is based on a gross rated WH energy, that is, the ram weight multiplied by whatever stroke is observed. A unique feature of diesel hammers is that the combustion force causing the ram to rise to the top of its stroke is simultaneous with impact and also helps to drive the pile. The combustion force offsets approximately all energy losses due to mechanical friction.

Energy ratings for diesel hammers may be taken as the ram weight multiplied by the observed stroke. Most open-top diesel hammers have markings allowing ram stroke to be observed readily. Closed-top diesels have bounce chamber pressure gages that relate directly to ram stroke.

<sup>11</sup> M. T. Davisson and V. J. McDonald, "Energy Measurements for a Diesel Hammer," *Symposium on Deep Foundations*, ASTM Special Technical Publication 444 (1968) pp 295-337.

**Consistency of Performance.** Most diesel hammers do not have fuel injectors and throttle systems (fuel pump rack adjustment) and depend on impact atomization of fuel. Hence, their stroke varies from low values in easy driving to high values in hard driving. However, the stroke values at final driving may be variable from pile to pile. One of the objections engineers have regarding diesel hammers is this inconsistent performance. Diesel hammers with fuel injectors and throttle systems, however, can be adjusted at final drive so that the same stroke is observed for all piles driven. Hammers of this type are fully reliable and no valid objections can be made to them.

The hammer manufacturer's operation and maintenance manual should be obtained for reference on details. The consistent full energy operation of the hammer at final driving can be readily verified by observing stroke and blow rate; these serve as an adequate performance check. For closed-top diesels lifting will occur at peak energy output; they should be operated just below the point of lifting. Open-top diesels should never be over-stroked because the ram can fly out of many of the models in common use, causing danger to the pile crew.

## HAMMER CUSHIONS

Hammer cushions (also called capblocks and dollies) are used to prevent excessive stresses in the hammer. Unfortunately, they also influence hammer output. A hammer with a soft cushion such as wood can be used to drive a pile to refusal; by replacing the wood with a harder cushion such as aluminum and mica discs, the pile will begin to penetrate under additional blows of the hammer. Therefore, uniformity of operation can be achieved only if the cushion block is held constant throughout *all* pile driving which includes test piles and indicator piles.

The engineer should either specify the cushion block size and material or be certain that whatever type of cushion is used at the start of a job is used throughout the entire job. Each hammer manufacturer specifies in detail the various cushion elements considered standard for each hammer. The hammer manufacturer's operation and maintenance manual should be obtained for reference.

It is the duty of the inspector to determine and

record the details of the cushion being used, as follows:

1. Plan dimensions and height. Record diameter of hole in center; if any.
2. Materials used and thickness of each disc if laminated.

Cushion elements are expendable. A wood cushion may last for one pile only, whereas an entire job may be driven with a single aluminum-micarta block. When the cushions deteriorate, they should be replaced.

Pile cushions, generally plywood, are commonly used on concrete piles. Their purpose is to protect the pile, but they have the same effect on pile driving as the hammer cushion. Therefore, it is the duty of the inspector to observe and record details of the pile cushion in the same manner as for the hammer cushion.

During production driving there may be reason to change cushion elements. The engineer should be involved in approving any change because the final driving criterion must also be changed accordingly. Criterion changes may be determined by wave equation analyses or by driving 3 to 6 piles with one cushion intermixed with 3 to 6 piles with the proposed cushion for purposes of comparing average driving records and arriving at comparable criteria.

## DRIVE HEADS

Drive heads or drive caps adapt the hammer to the pile and rest directly on the pile except when a pile cushion is inserted between them. The hammer cushion rests directly on the drive head. The inspector should observe and record (a) manufacturer's model number of drive head, (b) the approximate weight of drive head, and (c) photographs of the drive head (optional). Drive heads may be freely substituted by the contractor if the weight does not vary substantially. In case of a weight change exceeding 20 to 30 percent, the engineer should be notified

because the final driving criterion may have to be changed. A wave equation analysis can be used to determine if a change is warranted.

A very important item for the inspector to observe is the fit of drive head and pile. A poorly fitting drive head contributes substantially to pile head damage; this in turn produces a cushioning effect similar to that of the hammer cushion. Excessive pile head damage should be reported immediately to the engineer. The causes of pile head damage are:

1. Poorly fitting drive head.
2. Structural inadequacy of the pile.
3. Improper matching of hammer and hammer cushion to the pile.

Item 1 is strictly the contractor's problem, and he should be made to provide an adequate drive head. Items 2 and 3 are matters of design, which the engineer can evaluate by utilizing the wave equation analysis of pile driving.

## HAMMER OPERATION ON BATTERS

When placed on a batter, hammer rams are subjected to more friction than exists in the vertical position due to friction on the ram guides, packing, and piston rings. Shortening of the vertical stroke and the extra friction causes a marked decrease in hammer efficiency. Therefore, the final driving criterion in terms of blows per inch must be adjusted upward relative to vertical piles. Adjustment of the final criterion should be made by the engineer.

Single-acting hammers are affected most by operation on a batter. Differential and double-acting hammers are also subject to friction, but are less affected because that portion of the gross energy rating (approximately 50 percent) due to the downward steam force is independent of batter. Diesel hammers are less affected by friction than steam hammers, and closed-top diesels are affected less than open-top diesels because the effect of the bounce chamber is essentially independent of batter.

## APPENDIX II

### VIBRATORY PILE DRIVERS

#### INTRODUCTION

Vibratory pile drivers were conceived and their development initiated during the decade before World War II. Since World War II, vibratory drivers have been utilized in Russia, Germany, France, Japan, and the United States. At the present time the United States is the technological leader in the development of vibratory drivers, although a driver of French origin is widely used.

The mechanics of vibratory pile driving are different from those of impact pile driving and for this reason are treated separately in this manual. The mechanics of impact pile drivers have remained essentially the same since their original usage which probably predates recorded history. The drop-hammer is nothing more than a mechanized version of a manually operated hammer; steam and air-powered impact drivers are nothing more than the speeding up of the drop-hammer operation. Developments in impact pile driving have been primarily in terms of blow rate which has the effect of decreasing the amount of time required to drive a pile.

In impact pile driving the pile penetrates during the time impact is taking place and very shortly thereafter. In between hammer blows the pile is essentially at rest. Vibratory drivers, however, produce a steady state up and down motion (longitudinal vibration) of the pile. Vibratory drivers both push downwards and pull upwards on a pile, whereas impact drivers generate only downward forces on a pile. In the following sections of this manual, the mechanics of vibratory drivers will be described and then discussed in terms of final driving criteria. Then, driving operations utilizing vibratory driving are discussed and inspection procedures described. Finally, several special features of vibratory drivers are described.

#### MECHANICS OF VIBRATORY PILE DRIVERS

**Machinery.** The most common mechanical configura-

tion of vibratory pile drivers is illustrated schematically in Figure 14. The pile is rigidly clamped to an oscillator with a hydraulic clamping device. The oscillator may, for example, have a length of 6 ft and weigh 1000 to 1500 lbs. The majority of the weight of the vibratory driver is isolated from the oscillator by a specially designed isolation spring. The purpose of the isolation spring is to prevent, to the extent possible, the transmission of vibrations from the oscillator to the pile driving leads and the crane boom.

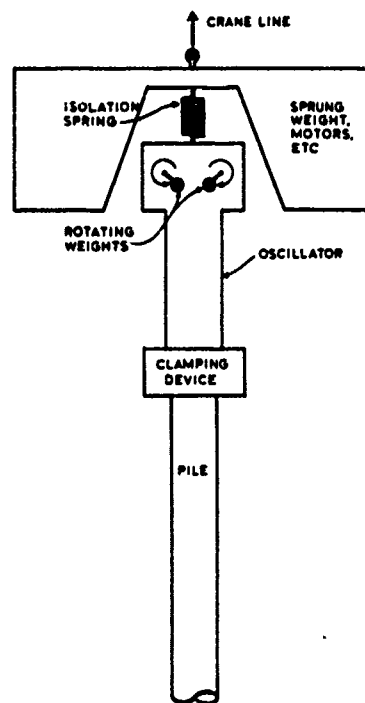


Figure 14. Schematic of Vibratory Drivers.

The weight of the equipment exclusive of the oscillator is referred to as the sprung weight. This consists primarily of the engines, or loaders, and associated equipment. Internal combustion engines and electric and hydraulic motors have all been used to supply the power to drive the oscillator. The entire weight of the vibratory driver is lifted by a cable from the crane. For driving bearing piles the driver is commonly fitted to pile driving leads similar to those for impact hammers.



The oscillator contains counter-rotating eccentric weights that are phased in such a way that centrifugal forces parallel to the pile are additive whereas lateral forces cancel. Drive shafts or drive chains from the power source cause the eccentric weights to rotate thus producing an oscillating axial force,  $F$ , expressed as

$$F = F_0 \sin \omega t,$$

in which  $F_0$  is the sum of the centrifugal forces produced by the rotating weights,  $\omega$  is the angular velocity of the weights, and  $t$  is time.

Control systems are usually located on the ground or on the pile driving crane adjacent to the crane operator. Vibratory drivers powered by internal combustion engines are usually self-contained and require no additional ground support equipment. However, electrically and hydraulically powered vibratory drivers require generators and hydraulic pumps either on the ground or mounted on the pile driving crane.

**Output Force.** Forces delivered to the pile consist of the sinusoidal oscillator force plus the dead weight of the driver itself. The nature of the forces delivered to the pile is shown schematically on Figure 15. The dashed line indicates the weight of the driver which acts constantly. Superimposed on the weight of the driver is the sinusoidal oscillator force which produces both compression and tension on the pile. It is seen that the pile is subjected to a net tension load part of the time. Forces produced by the oscillator average to zero with respect to time; the average force applied to the pile is simply the dead weight of the driver.

The oscillating force produces longitudinal vibrations in the pile. Up and down motions (vibration amplitude) in the pile help overcome pile-soil skin friction, thus allowing the dead weight of the driver to push the pile into the ground.

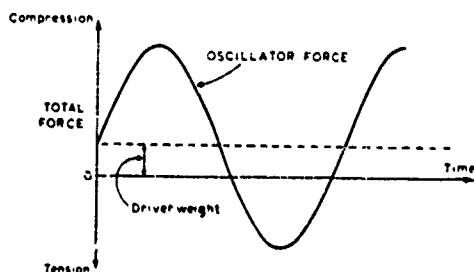


Figure 15. Force Output of Vibratory Drivers.

**Power.** Soil resistance to pile vibration consumes energy and thus behaves as a damping element. Power must be supplied continuously to the oscillator in order to maintain pile vibration. If a given level of vibration amplitude is desired, vibratory drivers must produce whatever energy is required to produce that amplitude. The power required is a function of the pile, soil, and frequency. Therefore, vibratory drivers are variable energy devices producing whatever output energy is required within the limits of the available energy (engine horsepower). This is in contrast to impact drivers wherein the energy per blow is essentially constant.

In Figure 16 the horsepower required by a pile-soil-driver system is plotted against the frequency of vibration. Power requirements increase with frequency except for the peak shown on the curve labeled resonance. The resonance in this case is for the oscillator and pile in longitudinal vibration. Resonance is a fundamental characteristic of any vibrating system; in this case it is controlled primarily by the length of the pile and secondarily by the weight of the oscillator and clamp; soil has a damping effect, and modifies the resonant frequency very little. The resonant frequency for the length of piles commonly used is in the range of 50 to 150 cps.

All but one of the available vibratory pile drivers are non-resonant (subsonic) devices in that they operate at approximately 1/4 to 1/3 of the resonant frequency. Such drivers will be referred to as non-resonant drivers. Generally their frequency ranges from 5 to 40 cps with a majority of them operating in the range of 13 to 30 cps. Operation at resonance (sonic) is a patented process and only one such driver exists, the Bodine Resonant Driver.

In the case of the Bodine Resonant Driver, it is possible to adjust frequency and power to operate at point 1 on Figure 16. With a slight increase in

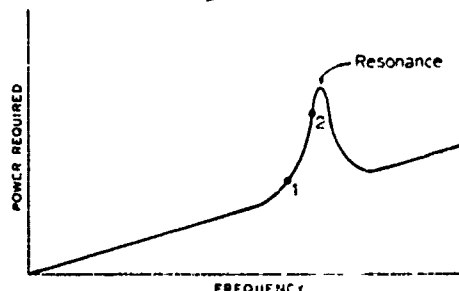


Figure 16. Power Consumption of Vibratory Drivers.

frequency and a large increase in power, it is possible to operate at point 2. The advantage of operating at point 2, just below the resonant peak, is that power transmission is at maximum efficiency. A given level of vibration amplitude in the pile can be achieved more easily at resonant than at non-resonant frequencies. It should be noted that the Bodine Resonant Driver is a variable frequency device, whereas the non-resonant drivers are essentially fixed-frequency devices.

Power requirements are also a function of the peak force delivered by the oscillator. The higher the oscillator peak force, the higher the power that is required. The maximum rate of penetration should be associated with the greatest horsepower that can be delivered to drive the pile. For a given oscillator with a given peak force capability, it can be seen from Figure 16 that the resonant driver has the highest capability for driving. All non-resonant drivers are mechanically less efficient.

**Rating of Drivers.** The foregoing discussion indicated that the capability of a given vibratory driver is a function of the output force of the oscillator. For mechanical oscillators such as those described, the output force is proportional to the square of frequency. Therefore, rating a vibratory driver in terms of peak force is not sufficient; the rating must also

include the frequency at which the force applies. In the case of the Bodine Resonant Driver, a frequency of 100 cycles per second has been arbitrarily chosen as the reference standard; this is approximately the average operating frequency for the machine. For non-resonant drivers the maximum peak force for each model has been given which corresponds to the highest frequency that the driver can operate.

The vibratory drivers generally available in the United States are listed according to make and model in Table 2. For each driver, the total weight of the machine, including the oscillator and the sprung weight, is given, as is gross available horsepower. Also given in Table 2 are the frequency range within which each machine can operate, and the rating consisting of peak force and the associated frequency. It can be seen from Table 2 that the highest force rating and the highest available power are for the Bodine Resonant Driver. The non-resonant drivers approach the oscillator output force rating of the Bodine, but have considerably less power available. At the present time (1971) the Bodine Resonant Driver is by far the most capable vibratory driver available. Non-resonant drivers can be developed that will equal or exceed the capabilities of the present Bodine drivers, but they will require force outputs considerably higher than that of the Bodine machine.

Table 2  
Rating of Vibratory Drivers\*

Make	Model	Total Weight, kips	Gross Available Power, HP	Frequency, CPS, (hz)	Peak Force** Frequency	kips CPS (hz)
Bodine	B	22	1,000	0-150	63/100	
					87/100	
					121/100	
					158/100	
					174/100	
MKT	VD10	9.5	110	27.5-31	112/31	
	VD14	10.8	110	27.5-31	141/31	
PTC (Foster)	2-17	6.2	34	18-21.5		
	2-35	9.1	70	15-18.5	62/19	
	2-50	11.2	100	11.5-17	101/17	
	2-60					
	2-75					

\* Models generally available in USA.

\*\* Peak forces are current maximums, and may readily be changed in some models by changing eccentric weights.

## DRIVING CRITERIA

**Driving Data.** A certain level of power input to the oscillator is required before pile penetration commences. Thereafter, increases in power lead to increases in the rate of pile penetration. This is analogous to driving a pile with an impact driver where the drop of the hammer in a drop-hammer or the energy per blow of a steam or air-powered hammer is increased. It would be found that a certain energy rating is required before the pile will drive at all. Thereafter, as energy is increased, the penetration of the pile for each blow increases.

In the case of impact driving, penetration is measured in terms of distance per blow. In the case of vibratory driving, penetration can be measured in terms of rate (velocity) of penetration. If a vibratory driver is operating at 10 cycles per second and the rate of penetration is 10 inches per second, then penetration can also be stated as 1 inch per cycle. Therefore, rate of penetration is analogous to the pile set-per-blow of impact driving.

A relationship exists between power, rate of penetration, and pile load capacity. Observations of power and rate of penetration at final driving are, therefore, important for evaluating pile capacity. The rate of penetration is best determined at final driving by using a stopwatch to time the last few feet or inches of driving. Data on power consumed by the oscillator-pile-soil system can be obtained by means of an engine calibration chart for internal combustion engines, or by a power meter in the case of electrical equipment. For hydraulic equipment, power can be determined from measurements of flow and hydraulic pressure.

Oscillator frequency is another important parameter that can be observed during driving. Oscillator frequency is a multiple of engine speed and can be obtained from a tachometer. The frequency of vibratory driving is analogous to blow rate for impact driving.

In summary, the three items that can be observed during driving with the vibratory driver are: (a) power, (b) rate of penetration, and (c) frequency. A practical dynamic formula for estimating pile load capacity must deal with these observable parameters.

**Dynamic Formula.** For many years piles have been installed to a required capacity based upon a dynamic

pile driving formula in conjunction with conventional impact hammers. The use of a dynamic pile driving formula to determine pile capacity is usually limited to small routine projects or where experience has demonstrated that the formula is applicable for the type of pile and sub-soil conditions involved.

On large projects, representative piles are usually load tested to determine the driving criteria. The driving formula then becomes a useful index to reflect the variation in sub-soil conditions usually encountered on any construction site, and serves as a guide for obtaining uniform driving resistance. The practicality of the foregoing procedure is indicated by its widespread use. A need exists for a driving formula applicable to vibratory drivers analogous to those used with impact hammers.

The basis for practically all common dynamic pile driving formulas is the simple energy relationship:

$$\text{Energy Supplied} = \text{Energy Used}$$

Because some of the energy is consumed by losses, the following statement is more appropriate:

$$\text{Energy Supplied} = \text{Energy Used For Pile Penetration} + \text{Losses}$$

Letting  $E$  represent the energy supplied and  $R_u$  the ultimate pile load capacity, the above statement becomes

$$E = R_u (S + S_L),$$

where  $S$  is the pile final permanent set per blow and  $S_L$  is an empirically determined "set" that represents all losses. By rewriting the expression as

$$R_u = \frac{E}{S + S_L}, \quad (\text{Eq. 1})$$

it takes the form of most traditional formulae, such as the Engineering News Formula. A factor of safety must be applied to the above expression to establish the allowable load. It can be shown that a similar approach can be used to arrive at a formula for vibratory driving.

It is possible to develop a driving formula for vibratory drivers using the basic assumptions involved in common dynamic formulas for impact hammers.<sup>1,2</sup>

<sup>1,2</sup> M. T. Davison, "BRD Vibratory Driving Formula," *Foundation Facts*, Vol 6, No. 1 (1970) pp 9-11.

For vibratory driving the input data will be developed for one cycle of oscillation, analogous to one blow of an impact hammer. Energy (E) becomes horsepower (Hp) divided by frequency (f), and set (S) becomes rate of penetration ( $r_p$ ) divided by frequency:

$$E = \frac{Hp}{f}$$

$$S = \frac{r_p}{f}$$

Considering that one horsepower equals 550 ft-lb/sec and substituting in equation 1, we get

$$R_u = \frac{\frac{Hp}{f} 550}{\frac{r_p}{f} + S_L}$$

or 
$$R_u = \frac{550 Hp}{r_p + f S_L} \quad (\text{Eq } 2)$$

where:

- $R_u$  = ultimate pile capacity, lbs
- $Hp$  = horsepower delivered to pile
- $r_p$  = final rate of pile penetration, ft/sec
- $f$  = frequency, cps
- $S_L$  = loss factor, ft/cycle.

Where the pile capacity is low and the rate of penetration high, another power term should be added to the numerator, namely, the weight of the driver (W) times the rate of penetration. This accounts for the kinetic energy of the driver itself. Therefore, the complete formula becomes:

$$R_u = \frac{550 Hp + W r_p}{r_p + f S_L} \quad (\text{Eq } 3)$$

All terms in the resulting expression are known from driving data, except the loss factor  $S_L$  which is determined empirically just as it has been for dynamic formulas for impact driving.

Loss factors will vary with soil conditions and the power transmission characteristics of the pile, and should be determined from the results of load testing to failure of piles driven with the vibratory driver in question. Thus the suggested vibratory driving formula can be calibrated for various actual pile driving conditions. The formula can be modified to give the allowable pile load by applying a suitable factor of safety ranging from 2 to 3 based upon judgement,

experience and the degree of accuracy of the loss factor value. The formula applies to friction piles, not point bearing piles.

In applying the formula, the required rate of penetration for a given design load can be determined for different combinations of brake horsepower and frequency. Thus like most conventional dynamic formulas, it can assist the contractor and engineer in achieving relatively uniform results in the development of pile capacity under the normal variations in subsoil conditions.

**Resonant Driving.** For the Bodine Resonant Driver, the power output of the gasoline engines used to power it can be calibrated against manifold vacuum (inches of mercury) and engine speed (rpm). A typical calibration chart is presented as Figure 17; all mechanical losses have been deducted so that only the power consumed by the oscillator-pile-soil system is represented. Engine speed and manifold vacuum are obtained from the instrument control panel for the driver.

The chart on Figure 17 is entered with manifold vacuum at the bottom of the chart, and is followed

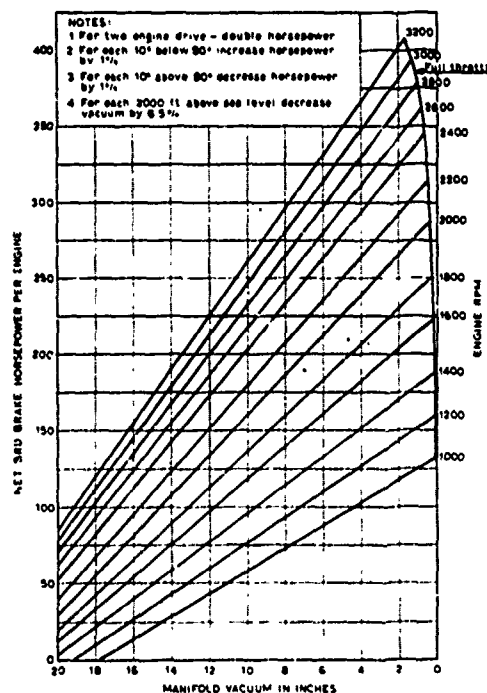


Figure 17. Power Chart for the Bodine Resonant Driver.

vertically until it intersects the line corresponding to engine rpm. Then the chart is read horizontally to the net brake horsepower per engine. There are two engines on the Model B Bodine Resonant Driver. Frequency is a multiple of engine rpm and is available from a chart on the control panel tachometer.

The final item, rate of penetration, is obtained by using a stopwatch to time the last few feet or inches of driving.

In the case of the Bodine Resonant Driver, several typical values for loss factor are available based upon load tests to failure of piles driven with the Bodine machine. These typical values of loss factor are presented in Table 3. The available data did not include cohesive soils. The loss factors in Table 3 may be used as a guide for estimating ultimate pile capacity.<sup>13</sup>

**Non-Resonant Driving.** A relatively small number of bearing piles have been driven with non-resonant vibratory drivers. This fact, coupled with the fact that almost all non-resonant drivers lack a power measuring device, is the reason why very little data is available for evaluating loss factors in the foregoing dynamic formula. There is no reason why non-resonant drivers cannot be instrumented to provide the same driving data available for the Bodine Resonant Driver. If the non-resonant drivers are instrumented, the foregoing dynamic formula should be applicable although the loss factors are likely to be different from those in Table 3.

## DRIVING OPERATIONS

**Preconstruction Organization.** The entire discussion given for conventional impact driving operations applies also to vibratory pile driving operations, the only exceptions being the driving equipment and several of the data forms. With regard to inspection, there is still a need for only one man per driving rig. With respect to equipment, the only additional items required are stopwatches. In order to cover a wide range of pile penetration rates, it is suggested that one watch reading in minutes to 0.01 minute be used

Table 3

Loss Factor ( $S_L$ ) ft/cycle, for Bodine Resonant Driver

Soil at Pile Tip	Closed-end Pipe	H-piles
Loose silt, sand, or gravel	0.0008	-0.0007*
Medium dense sand or sand and gravel	0.0025	0.0025
Dense sand or sand and gravel	0.008	0.007
Rock	Formula not applicable	

\* The loss factor is negative for H-piles in loose granular soils; this is an indication of soil behavior and not a defect in theory. Loose sands, silts and soft clays are easily disturbed during driving and allow easy pile penetration. With reconsolidation, pile capacity increases, and such behavior is reflected in the ultimate pile load capacity determined by static test. Negative loss factors also occur with conventional dynamic formulas under similar soil conditions.

to time the entire driving operation, and that a stopwatch reading to 0.1 second be used to time the last few feet or few inches of penetration.

As with impact drivers, the inspection agency should obtain the manufacturer's operating and maintenance manual for the vibratory driver being utilized by the contractor. The inspection agency should know prior to construction, and at all times during construction, the items of information shown on the vibratory driver equipment data form on Figure 18. The circled numerals on the data form labeled "Vibratory Pile Driving Equipment Data" correspond to the numerals in the list of explanations below:

- 1 Circle the rig number to which this equipment sheet applies. This is the rig number adopted in preconstruction organization.
- 2 The equipment data sheets for each rig are numbered consecutively throughout the job.
- 3 Date on which the equipment data sheet goes into effect.
- 4 Time of day on which the equipment data sheet goes into effect.
- 5 The inspector.
- 6 The equipment operator.
- 7 Data on these items should be printed when the form is printed.
- 8 Data such as that given in Table 2 should be obtained from the manufacturer's manual and placed in these spaces.
- 9 The weight and length of all unsprung parts are

<sup>13</sup> M. T. Davisson, "BRD Vibratory Driving Formula."

# VIBRATORY PILE DRIVING EQUIPMENT DATA RECORD

RIG: 1 2 3 ①

PROJECT \_\_\_\_\_  
 LOCATION \_\_\_\_\_  
 OWNER ⑦ \_\_\_\_\_  
 ENGINEER \_\_\_\_\_  
 CONTRACTOR: \_\_\_\_\_

SHEET NO ② OF \_\_\_\_\_  
 DATE ③ \_\_\_\_\_  
 TIME ④ \_\_\_\_\_  
 BY ⑤ \_\_\_\_\_  
 OPERATOR ⑥ \_\_\_\_\_

DRIVER MAKE _____	} ⑧
DRIVER MODEL NO. _____	
RATING _____	
TOTAL WEIGHT _____	
OSCILLATOR	LENGTH _____
	WEIGHT ⑨ _____
	TYPE _____
FOLLOWER	LENGTH _____
	WEIGHT _____
	TYPE _____
CLAMP	LENGTH _____
	WEIGHT _____
	TYPE _____
ADAPTER	LENGTH _____
	WEIGHT _____
	TYPE _____
SPECIAL ADAPTER	LENGTH _____
	WEIGHT _____
	TYPE _____
GEAR RATIO ⑩ _____	
LEADS	NQ ⑪ _____ YES _____ ft WEIGHT _____
RIG	CRANE MODEL _____
	CAPACITY, TONS _____
	BOOM LENGTH _____
	COUNTERWEIGHT _____

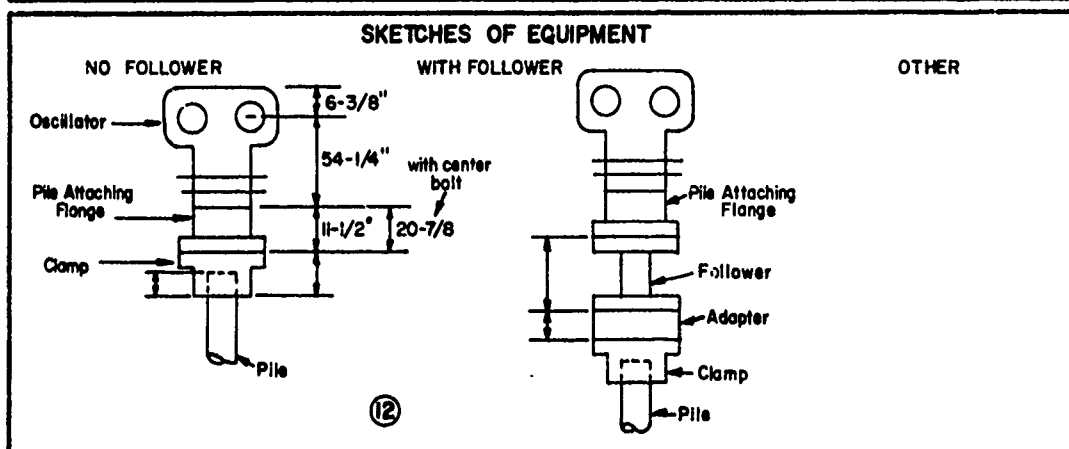


Figure 18.

of critical importance. This consists of everything from the oscillator to the pile. Therefore, the length and weight of oscillator, follower if any, clamp, adapter, and special adapters, if any, should be inserted in these spaces.

- 10 The gear ratio is the ratio between engine speed and oscillator frequency. With this ratio engine speed can be used to obtain oscillator frequency or vice versa.
- 11 Space is provided to record information on the leads and the pile driving rig if it is of interest for the project.
- 12 Sketches of the unsprung parts can be helpful. The examples shown apply to the Bodine Resonant Driver; configurations with and without a follower are shown.

**Driving Operations.** During driving, the inspector's primary duty is to record the time for each unit of penetration; this may be for 5 ft of driving, per foot of driving, or per inch of driving. This information must be obtained at the time of driving or it is forever lost. Therefore, a suitable data form for the driving record is a practical necessity. Because vibratory drivers are variable energy devices, it is also necessary that items related to power be recorded versus depth. In the case of internal combustion engines, the required observations are engine speed and manifold vacuum.

An example of an individual driving record is given as Figure 19. As shown, it applies to the Bodine Resonant Driver, but it can very easily be adapted to other types of vibratory drivers by substituting the appropriate measurements related to power. Pertinent items on Figure 19 are identified by circled numerals which correspond to numerals in the following list of explanations:

- 1,2,3 Production Day Number, Rig Number, and Pile Designation adopted during preconstruction organization described previously.
- 4 Furnish length is the actual length of pile under the hammer. This length is available at the top of each pile according to the pile marking system described previously. See item 24 below concerning trimming tops of spliced piles.
- 5 X-Section is the description of the pile cross-section such as HP 12 x 53 for an H-pile, and 12.75" OD 0.250" for a pipe-pile. This is useful for projects where more than one

pile cross-section is utilized, but may be ignored where only one cross-section is used throughout a project.

- 6 Time Start is the hour and minute when the hammer first starts driving the pile on a given day.
- 7 Time Finish is the hour and minute when the hammer strikes the last blow on a given day for a given set-up of the hammer on the pile. Redriving of a pile is treated as a complete separate drive with respect to both start and finish times.
- 8,9 No comment required.
- 10 Depth below ground.
- 11 Total driving time to reach the depth indicated. Use stopwatch reading to 0.01 minute.
- 12 Engine rpm or oscillator frequency. Obtain from tachometer on control panel.
- 13 Manifold vacuum. Obtain from gage on control panel.
- 14 Number of engines producing driving power.
- 15 Approximate ground elevation at location of the pile.
- 16 The final depth of penetration of the pile below ground. Depth should be measured from ground elevation, item 15 above.
- 17 The final rate of penetration in, e.g., seconds per foot or seconds per inch. Use stopwatch reading to 0.1 second.
- 18 Frequency of the oscillator at final driving, cps or hz.
- 19 Horsepower at final driving determined from chart.
- 20 Total driver operating time. Use stopwatch reading to 0.01 minute.
- 21 Remarks should cover reasons for delays, other than for splices, and any unusual or non-routine items noticed during the driving operation. Examples would be pile damage, noting drift of the pile off center after hitting an obstruction, reasons for rejection, etc.
- 22 In some cases piles are driven through overburden. The length so driven is the difference between ground elevation and cut-off elevation.
- 23 The depth to which drilling, jetting or spud-

PILE PENETRATION RATE DATA RECORD										REDRIVE (28)		REJECT (26)	
PROJECT: LOCATION: OWNER: (27) ENGINEER: CONTRACTOR:										PROD. DAY NO. (1) RIG NO. (2)			
										PILE DESIG. (3)			
										FURNISH LENGTH (4)			
										PILE X-SECT: (5)			
										TIME START (6) FINISH (7)			
										DATE: (8) BY (9)			

DEPTH Feet	TIME Minutes	RPM FREQ.	VAC. in Hg	No. Eng	DEPTH Feet	TIME Minutes	RPM FREQ.	VAC. in Hg	No. Eng	DEPTH Feet	TIME Minutes	RPM FREQ.	VAC. in Hg	No. Eng
10	(11)	(12)	(13)	(14)										
0														
5					60					100				
10														
15														
20					65					105				
25														
30					70					110				
35					75					115				
40					80					120				
45					85					125				
50					90					130				
55					95					135				

REMARKS: (21)	GRND ELEV. (15)
	PENETRATED LENGTH (16)
	(17) SECS./ FREQ. (18) HZ
DROVE THRU O'BURDEN (22) FT DRILL BIT/SPUD (23) FT SPLICE at (24) FT HP (19) DRIVING TIME (20)	

Figure 19.





- ding was performed prior to driving should be recorded. Indicate the applicable item by circling, or cross out the inapplicable items.
- 24 Note the pile footage marks at which splices were made. Note remaining furnish length of pile if the head is trimmed of damaged material prior to splicing.
  - 25 This item should be noted by an "x" if the record applies to redriving a pile.
  - 26 This item should be noted by an "x" if the pile has been rejected. The reasons for rejection should be stated under remarks.
  - 27 Information on these items should be printed at the time the form is printed.

The individual pile penetration rate records described previously are made under field conditions involving, perhaps, poor weather, plus airborne droplets of oil from the equipment. As a consequence, the individual records are often smudged, folded, and the data made only as legible as time permits. Further, the quantity of individual records can be voluminous where production rates are high. A form summarizing pertinent data for each pile is desirable to cut down on the number of documents that must be handled and to provide a clean legible record.

A data form labeled "Daily Summary of Vibratory Pile Driving" is presented as Figure 20: this covers the activities of one rig for one shift. The summary satisfies the requirements stated above, and also provides a means of keeping a diary on the activities of each rig. Pertinent items on Figure 20 are identified by circled numerals which correspond to the numerals in the following list of explanations

- 1 Production Day Number adopted during pre-construction organization described previously.
- 2 Driver model. Shortened designations can be used.
- 3,4,5 No explanations required.
- 6 Circle the day and shift number applicable. Circle the Rig Number adopted during pre-construction organization.
- 7 Give the pile plan numbers on which the piles covered by the summary are located. This is particularly useful on large jobs where a large number of pile plans are involved.
- 8 Sheet number of form on Figure 19 applicable to the piles listed.
- 9 Time of Day is the beginning time of each activity summarized, e.g., the time driving starts on a pile, the time a delay begins, or the time a rig starts an out-of-sequence move.
- 10 The designation on the pile plan.
- 11 Place an "x" in this column if a sheet pile is driven in interlock.
- 12 Furnish length is the actual length under the hammer. This length is available at the top of each pile according to the pile marking system described previously.
- 13 Number of engines or motors furnishing power to the oscillator.
- 14 Manifold vacuum; usually expressed in inches of mercury.
- 15 Engine speed in revolutions per minute.
- 16 Penetrated length is the length driven below ground. This should correspond to the depth below the elevation given as item 20, below.
- 17 The Bodine machine has a meter that gives rate of penetration; the readings can be inserted in this column. Warning; the meter is often inaccurate and stopwatch values should be relied upon.
- 18 Place an "x" in this column if the pile is being extracted. Use one line for driving and a separate line for extracting piles.
- 19 Total driving time from stopwatch reading minutes to 0.01 minute.
- 20 Approximate ground elevation at location of the pile.
- 21 Stopwatch reading at final driving, e.g., seconds per foot or seconds per inch. Use stopwatch reading to 0.1 second.
- 22 Horsepower determined from items 13-15.
- 23 Oscillator frequency determined from tachometer or from engine rpm and gear ratio.
- 24 Use for special items interest to a particular job.
- 25 Note any unusual events during driving. In particular given the reason for rejection of a pile at the time of driving.
- 26 Use an "x" to indicate that the pile was rejected at the time of driving.
- 27 Information on these items should be printed at the time that the form is printed.

The summary should be kept current with the driving. Further, the summary form is used in exactly the same manner and for the same purposes as the Daily Summary of Pile Driving, Figure 3 of this manual. The only additional item is that a delay may occur for changing of the vibratory driver equipment. When this occurs, a new vibratory pile driving equipment data form (Figure 18) must be filled out and the sheet number of this equipment data sheet placed on the notes regarding the delay. In this manner, it is possible to know at all times which vibratory pile driver and which configuration of unsprung parts are being used.

On completion of the summary form the inspector has completed his duty with respect to the driving operation.

**Inspection and Measurement.** The inspection and measurement of piling driven with vibratory drivers is no different from that for impact driving. All of the preceding discussions in this manual apply to piles driven with a vibratory driver. There is one additional inspection technique that is difficult for conventional impact driven piles, but is quite easy for vibratory driven piles, namely, pulling for inspection. Vibratory drivers are more efficient as extracting tools than they are as driving tools. The cost of pulling a pile with vibratory equipment is quite low because the equipment in the leads does not have to be changed as is ordinarily the case with conventionally driven piles. Thus, vibratory pile driving has an advantage in that piles of solid cross section can be inspected for structural integrity at a very reasonable cost.

## SPECIAL FEATURES

**Costs.** Both the purchase price and the operating costs of vibrating drivers greatly exceed those for ordinary impact drivers. In order for vibratory drivers to be competitive with impact drivers, it is necessary to increase production by a factor of 2 to 3 over that for conventional equipment. In situations where vibratory drivers have unique advantages, such as noise reduction, and where a job has special requirements corresponding to these unique advantages, then economics may play a secondary role.

**Pile Force.** Vibratory drivers generate forces in the pile which can be easily estimated, whereas the forces in piles driven with impact drivers require a wave

equation analysis for determination. In general, the forces induced in piles by vibratory drivers are much lower than those produced by impact pile drivers. This fact explains the inability to drive piles relative to impact drivers in many cases. The trend appears to be to increase the size and force rating of vibratory drivers; future vibratory drivers will probably produce pile forces equal to those for impact drivers.

**Friction Piles.** Friction piles receive their resistance from vertical forces along the sides of the piles. Because vibratory drivers are particularly efficient in producing up and down motion of the pile, they are efficient at overcoming soil-skin friction and penetrating into such soil conditions.

**Point Bearing Piles.** The mechanics of vibratory driving are that the oscillator causes up and down motions of the pile, which overcomes skin friction along the sides of the pile and allows penetration under the weight of the driver. However, when the soil encountered by the tip of the pile is sufficiently strong to support the weight of the driver penetration, rates become very low. The reason for this is that forces at the tip of piles driven with a vibratory driver tend to be very low, thus causing vibratory drivers to have a very low ability to punch into soils at the pile tip. Until this feature is modified, vibratory drivers will be at a disadvantage in producing the peak forces required to overcome high point bearing resistance.

The dynamic formula given for vibratory driving applies to friction piles, not point bearing piles. The load carrying capacity of point bearing piles driven with a vibratory driver is subject to question. Where the pile tip encounters sound rock and seats on the rock, then the bearing capacity can be quite high. However, where the pile encounters an obstruction, or rock that is soft or weak, the rock may be sufficient to support the weight of the vibratory driver, but insufficient to provide the required bearing capacity for the pile. In cases such as this, it is necessary that an independent check on bearing capacity be obtained. This can be done by re-driving each pile with an impact hammer to a criterion determined by a wave equation analysis. Although this is a two-stage driving process, it has been shown to be economical on several projects where the vibratory driver was particularly efficient at causing penetration to the bearing layer.

Because of the limited force available at the tip of the piles driven with vibratory drivers, H-piles are

likely to achieve more penetration in high point bearing conditions than would closed-end pipe piles. The reason for this is that the stress on the area of the pile tip is much higher for H-piles as a result of lower cross-sectional area. The H-piles should, however, have point reinforcement in order to prevent distortion from non-uniform contact with the bearing layer.

**Pile Clamping.** In the discussion of the mechanics of the vibratory driving, it was mentioned that the pile is firmly clamped to the oscillator. This is an essential feature of vibratory driving because the driver produces both compression and tension forces in the pile; in order to be effective, it must be firmly clamped to the pile. If the clamp slips heat will be produced at the clamp and the pile may fracture. In addition, the effectiveness of the vibratory driver will diminish.

It is possible to set a vibratory driver on a pile and operate it without clamping. The pile will drive, but in a relatively inefficient manner, and not as deep as it would if firmly clamped.

**Types of Piles.** Because both clamping and tension forces are requirements of vibratory driving, steel piles must be preferred. In order to drive timber and concrete piles, it is necessary to have a method of clamping to them. Clamping has been achieved on timber and concrete piles for purposes of research; the piles have driven fairly well. At this time (1971) the clamping techniques available are not economical, and piles consisting of wood or concrete cannot be economically driven.

In the case of precast concrete, driving with vibratory drivers is quite inefficient compared to impact driving because of the tension that is inherent with vibratory drivers. Vibratory driving tends to produce a number of horizontal cracks in the pile, making it an undesirable driving method. In the case of prestressed piles, vibratory drivers are very effective until the tension force exceeds the prestress force in the pile. For difficult driving, vibratory drivers would have to produce forces so high that the prestress would likely be overcome and the pile would crack. Therefore, the vibratory drivers are likely to be useful with prestressed piles only in specialized cases where the soil conditions are especially conducive to vibratory driving.

**Followers.** Followers are longitudinal members placed between the vibratory driver and the top of

the pile to allow the driving equipment to reach below the pile driving crane and drive a pile through overburden. Followers can have a significant influence on the effectiveness of a vibratory driver. Considerable design attention should be given to followers before they are used. The methods of analysis given in Smart are recommended.<sup>14</sup>

**Pile Damage.** In general, vibratory drivers cause considerably less damage to a pile during driving than impact drivers. This comes about because vibratory drivers operate with a controlled steady-state vibration and do not cause impact at the head of the pile. Further, the forces at the tip of the pile are considerably less than that for impact driving and, therefore, a much lower potential for damage exists. Because of the ability of the vibratory driver to pull a pile, it becomes a very effective tool for inspection. If a pile is pulled with a vibratory driver and found to be damaged, then almost certainly there is a fault in the design of the pile foundation, or the soil conditions are other than anticipated in the design. It is possible to damage the tips of H-piles with a vibratory driver, especially where cobbles or boulders are encountered or where the piles penetrate to a rock surface. Any H-pile damage by a vibratory driver would be magnified many times if an impact driver were used instead to drive the pile. In such conditions, point reinforcement is mandatory if the structural integrity of driven piles is to be maintained.

The ability of vibratory drivers to pull a pile can be used very effectively in soil conditions containing obstructions, cobbles, boulders, etc. above the bearing layer. When a pile encounters such an obstruction it is usually readily apparent; if the obstruction cannot be bypassed within a few minutes of driving effort, then driving should be stopped. The pile can then be pulled, and set in another location and driven. If another obstruction is encountered, the process can be repeated until the pile bypasses the obstruction and reaches the bearing layer. By this technique great economy can be achieved in the use of pile material. Further, it is possible to drive piles into the bearing layer whose structural integrity can be checked by pulling. Where the piles will not penetrate to the bearing layer even with a vibratory driver, then pre-drilling or other driving aids are required. The

<sup>14</sup> J. D. Smart, "Vibratory Pile Driving," Ph.D. Thesis, (University of Illinois, 1969).

foregoing procedure has been used with great economy on several projects; however, the design of the pile caps had to follow the driving so that the design was consistent with as-built pile locations.

**Noise.** The noise associated with vibratory driving does not involve impact, which is the principal source of noise from impact drivers. However, considerable noise comes from the engines supplying the power for vibratory driving. Engine noise is much less intense than that from impact, but it is nevertheless substantial. Human response to noise from vibratory driving seems to be more passive than is the case with impact driving. It is believed that a very high potential exists for decreasing engine noise with vibratory drivers. This probably can be accomplished much more readily than the reduction of noise from impact drivers. Therefore, vibratory drivers can be very useful in special situations where noise is objectionable.

**Ground Vibration.** Ground vibration from impact

driving can be substantial. Non-resonant vibratory drivers can also produce substantial ground vibration, especially where the operating frequency of the driver matches the resonant frequency of the site in question. It may be said in general that where ground vibration from impact driving is objectionable, low frequency vibratory drivers are also likely to be objectionable.

The Bodine Resonant Driver has a unique advantage with respect to reduction of ground vibrations because of the frequency range in which it operates. Operating frequencies of 80 to 120 cycles per second are normal for the Bodine machine and are considerably above the resonant frequencies of most sites. Under these conditions, significant ground vibrations tend to dissipate within a few feet from the pile being driven. The Bodine machine has been used in many cases where ground vibrations were objectionable.

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